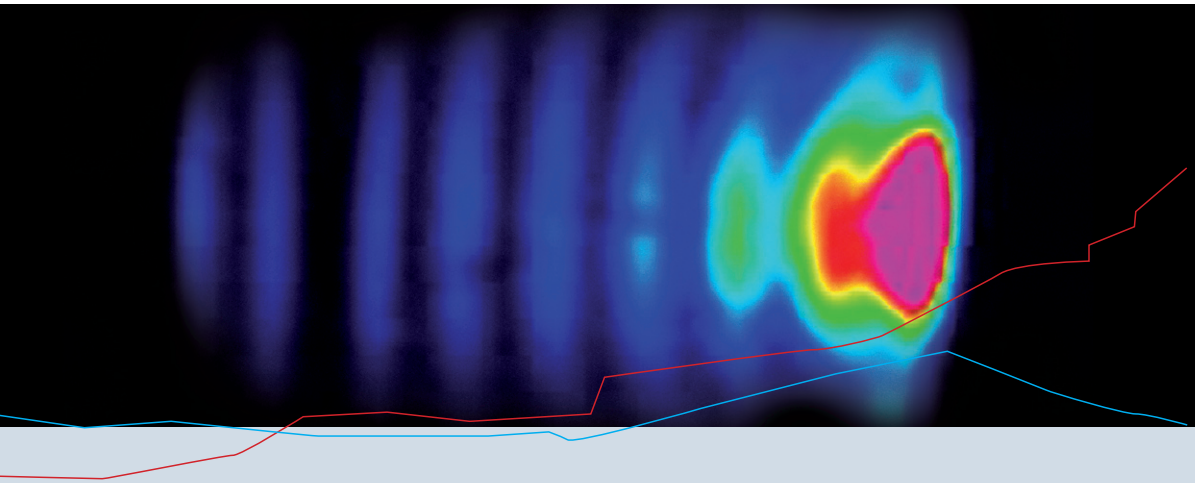
User's manual



FLIR R&D software suite 3.1

FLIR ResearchIR Max | FLIR ResearchIR | FLIR QuickPlot

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FLIR R&D software suite 3.1

User's manual

Publ. No. T559132 Rev. a582 – ENGLISH (EN) – January 11, 2012

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All products manufactured by FLIR Systems are warranted against defective materials and workmanship for a period of one (1) year from the delivery date of the original purchase, provided such products have been under normal storage, use and service, and in accordance with FLIR Systems instruction.

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This warranty shall be governed by Swedish law.

Any dispute, controversy or claim arising out of or in connection with this warranty, shall be finally settled by arbitration in accordance with the Rules of the Arbitration Institute of the Stockholm Chamber of Commerce. The place of arbitration shall be Stockholm. The language to be used in the arbitral proceedings shall be English.

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Quality assurance

The Quality Management System under which these products are developed and manufactured has been certified in accordance with the ISO 9001 standard.

FLIR Systems is committed to a policy of continuous development; therefore we reserve the right to make changes and improvements on any of the products described in this manual without prior notice.

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1 Notice to user

Typographical conventions

This manual uses the following typographical conventions:

- **Semibold** is used for menu names, menu commands and labels, and buttons in dialog boxes.
- *Italic* is used for important information.
- `Monospace` is used for code samples.
- UPPER CASE is used for names on keys and buttons.

User-to-user forums

Exchange ideas, problems, and infrared solutions with fellow thermographers around the world in our user-to-user forums. To go to the forums, visit:

http://www.infraredtraining.com/community/boards/

Training

To read about infrared training, visit:

- http://www.infraredtraining.com
- http://www.irtraining.com
- http://www.irtraining.eu

Additional license information

This license permits the user to install and use the software on any compatible computer, provided the software is used on a maximum of two (2) computers at the same time (for example, one laptop computer for on-site data acquisition, and one desktop computer for analysis in the office).

One (1) back-up copy of the software may also be made for archive purposes.

2 Customer help

General

For customer help, visit:

http://support.flir.com

Submitting a question

To submit a question to the customer help team, you must be a registered user. It only takes a few minutes to register online. If you only want to search the knowledge-base for existing questions and answers, you do not need to be a registered user.

When you want to submit a question, make sure that you have the following information to hand:

- The camera model
- The camera serial number
- The communication protocol, or method, between the camera and your PC (for example, HDMI, Ethernet, USB™, or FireWire™)
- Operating system on your PC
- Microsoft® Office version
- Full name, publication number, and revision number of the manual

Downloads

On the customer help site you can also download the following:

- Firmware updates for your infrared camera
- Program updates for your PC software
- User documentation
- Application stories
- Technical publications

3 Documentation updates

General

Our manuals are updated several times per year, and we also issue product-critical notifications of changes on a regular basis.

To access the latest manuals and notifications, go to the Download tab at:

http://support.flir.com

It only takes a few minutes to register online. In the download area you will also find the latest releases of manuals for our other products, as well as manuals for our historical and obsolete products.

4 Important note about this manual

General

FLIR Systems issues generic manuals that cover several software variants within a software suite.

This means that this manual may contain descriptions and explanations that do not apply to your software variant.

NOTE

FLIR Systems reserves the right to discontinue models, software, parts or accessories, and other items, or to change specifications and/or functionality at any time without prior notice.

5 Installation

5.1 System requirements

Required operating system

One of the following:

- Microsoft Windows XP Pro, with Service Pack 3 (SP3), 32 bit.
- Microsoft Windows Vista, with Service Pack 1 (SP1), 32 bit.
- Microsoft Windows Vista, with Service Pack 1 (SP1), 64 bit.
- Microsoft Windows 7, 32 bit.
- Microsoft Windows 7, 64 bit.

Recommended camera models and camera software releases

For a list of recommended and supported cameras, and camera software releases, go to http://support.flir.com.

Required hardware

- Personal computer with an Intel 2 GHz MHz Pentium processor (dual core) or an AMD Opteron, AMD Athlon 64, or AMD Athlon XP processor (dual core).
- 1 GB of RAM, or greater.
- 20 GB of available hard disk space.
- CD-ROM drive.
- Support for DirectX 9 graphics with:
  - WDDM driver
  - 128 MB of graphics memory (minimum)
  - Pixel Shader 2.0 in hardware
  - 32 bits per pixel.
- SVGA (1024 × 768) monitor (minimum, 1400 × 900 or higher recommended).
- Internet access (fees may apply).
- Audio output.
- Keyboard and Microsoft mouse, or a compatible pointing device.

5.2 Installation of FLIR R&D software suite 3.1

NOTE

- You must be an Administrator or a user with Administrative Rights to install the program.
- A complete installation consists of several subinstallations, some of which are from third-party vendors. Do not abort these subinstallations, as they are needed for the complete installation.
- A complete installation may take up to 30 minutes to complete.
- At a certain time during the installation, Microsoft warns repeatedly that the software has not passed Windows Logo testing. In all cases, select Continue Anyway. There is no risk involved with this.
- If you are asked to restart the computer during the installation, do so without removing the CD-ROM. The installation will resume after you have restarted.

Procedure

Follow this procedure to install FLIR R&D software suite 3.1:

1	Close down all applications.
2	Insert the FLIR R&D software suite 3.1 software CD-ROM into the CD-ROM drive on the computer. The installation should start automatically. Should the installation not start automatically, start Windows Explorer and double-click SETUP.EXE on the CD-ROM.
3	Follow the on-screen instructions.

6 Managing licenses

6.1 Registering your product

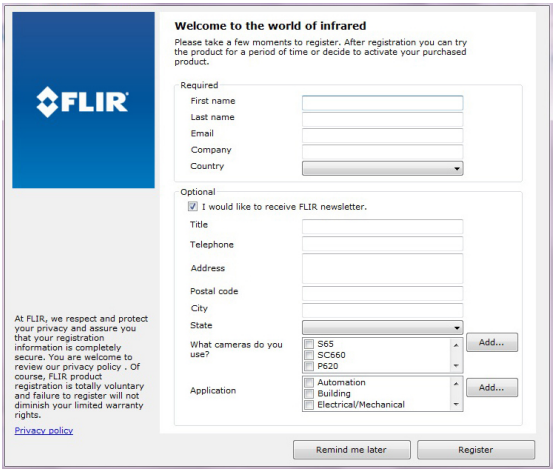
General

It is important that you register your product. By registering your product you are entitled to:

- Free program updates
- Free unlimited technical support at http://flir.custhelp.com
- Timely information about new releases

Figure

T638251;a1



Procedure

To register your product, fill in the required fields and click **Register**.

6.2 Activating your license

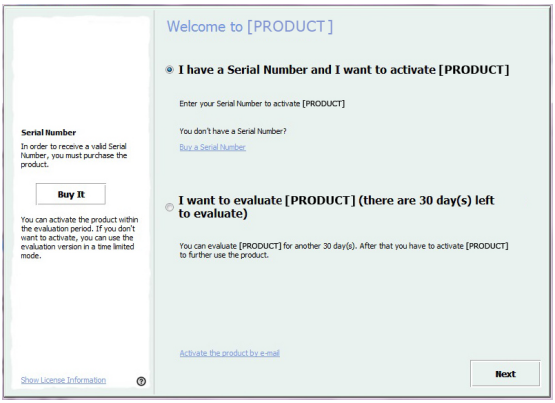
General

The first time you start FLIR R&D software suite 3.1 you will be able to choose one of the following options:

- Activate FLIR R&D software suite 3.1 online.
- Activate FLIR R&D software suite 3.1 by e-mail.
- Purchase FLIR R&D software suite 3.1 and receive a serial number for activation.
- Use FLIR R&D software suite 3.1 for free during an evaluation period.

Figure

T638252;a1


Welcome to [PRODUCT]
I have a Serial Number and I want to activate [PRODUCT]
Enter your Serial Number to activate [PRODUCT]
You don't have a Serial Number?
Buy a Serial Number
Serial Number
In order to receive a valid Serial Number, you must purchase the product.
Buy It
You can activate the product within the evaluation period. If you don't want to activate, you can use the evaluation version in a time limited mode.
I want to evaluate [PRODUCT] (there are 30 day(s) left to evaluate)
You can evaluate [PRODUCT] for another 30 day(s). After that you have to activate [PRODUCT] to further use the product.
Activate the product by e-mail
Show License Information
Next

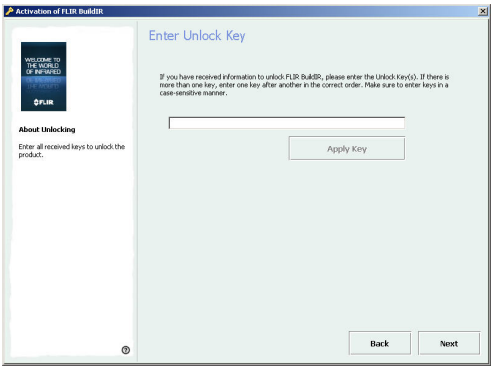
Activating FLIR R&D software suite 3.1 online

Follow this procedure:

1	Start FLIR R&D software suite 3.1.
2	In the web activation dialog box, select **I have a Serial Number and I want to activate FLIR R&D software suite 3.1**.
3	Click **Next**.
4	Enter your serial number, name, company and e-mail address. The name should be the name of the license holder.
5	Click **Next**.
6	Click **Activate now**. This will start the web activation process.
7	When the message **Online activation was successful** is displayed, click **Close**. You have now successfully activated FLIR R&D software suite 3.1.

Activating FLIR R&D software suite 3.1 by e-mail

Follow this procedure:

1	Start FLIR R&D software suite 3.1.
2	In the web activation dialog box, click **Activate the product by e-mail**.
3	Enter your serial number, name, company and e-mail address. The name should be the name of the license holder.
4	Click **Request Unlock Key by E-mail**.
5	Your default e-mail client now opens and an unsent e-mail with license information is displayed. **Send this e-mail without altering the content**. The main purpose of the e-mail is to send the license information to the activation center.
6	Click **Next**. The program will now start and you can continue working while waiting for the unlock key. You should receive an e-mail with the unlock key within two days.
7	When the e-mail with the unlock key arrives, start the program and enter the unlock key in the text box. See the figure below. T638430;a1 

6.3 Transferring your license

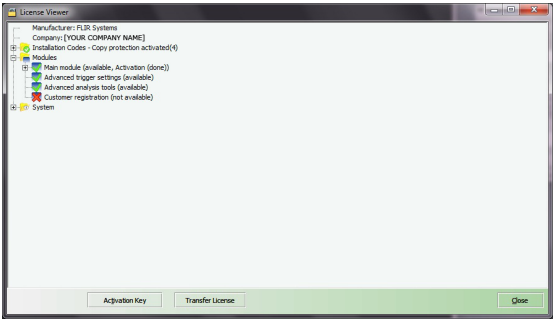
General

You can transfer a license from one computer to another computer, as long as you do not exceed the number of purchased licenses on one computer at the same time.

This lets you use the software on, for example, a desktop and a laptop computer.

Figure

T638254;a1



Procedure

Follow this procedure to transfer a license:

1	Start FLIR R&D software suite 3.1.
2	On the **Help** menu, select **Show license information**. This will display the license viewer shown above.
3	In the license viewer, click **Transfer license**. This will display a deactivation dialog box.
4	In the a deactivation dialog box, click **Deactivate**.
5	On the computer to which you want to transfer the license, start FLIR R&D software suite 3.1. As soon as the computer gets Internet access, the license will be automatically adopted.

NOTE

The adoption of licenses is based on a “first-come, first-serve” concept. This means that the *first* computer that gets Internet access automatically adopts the transferred license.

6.4 Updating your product

General

We regularly issue software updates and you can update the program using this update service.

Procedure

Follow this procedure to check for updates:

1	On the **Start** menu, select **Programs** > **FLIR Systems** > **FLIR R&D software suite 3.1** > **Check for updates**.
2	Follow the on-screen instructions.

NOTE

Some programs from FLIR Systems also support updating from within the application.

7 Getting started

7.1 Connecting a camera

General

You can connect a camera to your computer or your network, using one of the following methods:

- Ethernet
- FireWire
- USB.

If you have followed the installation instructions, connecting a camera will be a plug-and-play procedure, and the camera will be displayed in the top left corner of the program screen.

Recommended camera models

For a list of recommended and supported cameras, and camera software releases, go to http://support.flir.com.

NOTE

- Your firewall may block access to the camera. If so, allow access. There is no risk involved with this.
- FLIR ResearchIR Max supports having more than one camera connected to the software at the same time. However, a maximum of four camera windows can be displayed on one camera tab. If you want to add more cameras, you need to add them on additional camera tabs.

7.2 Acquiring an image or sequence file in real time

General

This section describes how you choose images and files using the file explorer pane. Using this method you can only work with images and sequence files in one folder at a time.

Procedure

Follow this procedure:

1	Start the program.
2	To select a camera, click **Select camera** in the top left corner, and choose the camera you want to use. The image will be automatically displayed in the image window.

NOTE

- When you start the program the next time, the last connected camera will be displayed in the live source control. To connect this camera, click **Connect**, or use the right-click menu.
- For an explanation of screen elements, see section 8 – Overview of screen elements on page 18.

7.3 Adjusting the image or sequence file

General

You can adjust an image or sequence file using three different adjustment methods, and you may need to try different methods to see which one suits your application the best.

Adjustment methods

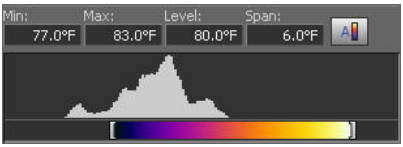
You can choose between the following adjustment methods:

1 **Auto**: The image or sequence file is automatically adjusted to display the best image brightness and contrast.
2 **Min**/**max**: The upper and lower temperature values are set explicitly, by using sliders or entering values in text boxes.
3 **Level**/**Span**: The temperature level is set explicitly, by using sliders or entering values in text boxes, and the span is set in the same way.

Note that methods 2 and 3 are identical with regard to what they do to the image or sequence file, but let you enter values in different ways.

Figure

T630412;a4



Procedure

Follow this procedure:

1	Go to the **Scale** pane.
2	Do one of the following: ▪ Click to auto-adjust the image. ▪ Enter values for **Min**/**max** or **Level**/**Span**.

NOTE

For an explanation of screen elements, see section 8 – Overview of screen elements on page 18.

7.4 Saving a sequence file or an image snapshot

About saving a sequence file

Prior to recording, you need to specify where you want to save your sequence files. You do this on the **Storage** tab.

When you have specified the path, the recorded sequence files will be saved in this location.

About saving an image snapshot

During the recording of a sequence file, you can at any time save an image snapshot as a *.jpg file. You do this by clicking the button on the recording toolbar. This saves the image snapshot to the designated location.

NOTE

For an explanation of screen elements, see section 8 – Overview of screen elements on page 18.

7.5 Locating images or sequence files

Procedure

Follow this procedure:

1	Click the **Organize** tab
2	To locate your images or sequence files, use the file explorer in the same way as you use Microsoft Windows Explorer. You can expand folders, select external drives, etc.
3	(Optional) To add an image or sequence file to the Quick Collection for later analysis, move the file to the Quick Collection pane using the right-click menu or a drag-and-drop operation.

NOTE

For an explanation of screen elements, see section 8 – Overview of screen elements on page 18.

7.6 Viewing images or sequence files

General

This procedure assumes that you have carried out Step 3 in the previous procedure.

Procedure

Follow this procedure:

In the Quick Collection pane, move the image or sequence file to the image window by double-clicking, using the right-click menu or using a drag-and-drop operation.

You can now view or play the file in the image window.

NOTE

For an explanation of screen elements, see section 8 – Overview of screen elements on page 18.

8 Overview of screen elements

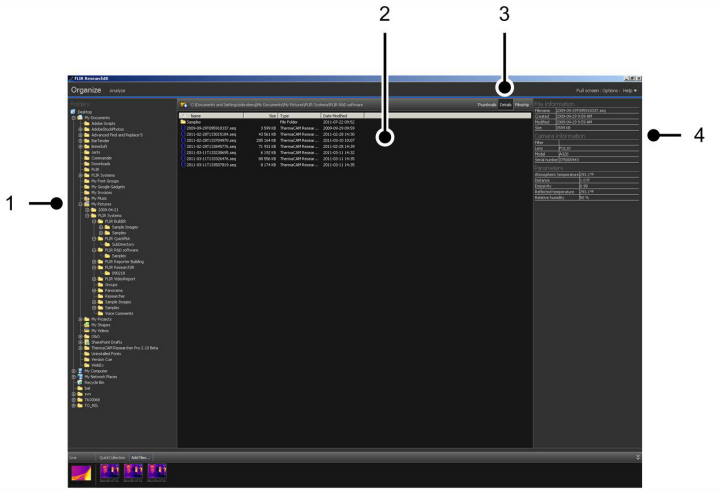
General

- Many functions and tools have tooltips that display basic help information. To display the tooltips, hold the cursor over the function or tool in question.
- To display the online Help, press F1.

8.1 *Organize* tab

Figure

T630400;a2



Explanation

This table explains the figure above:

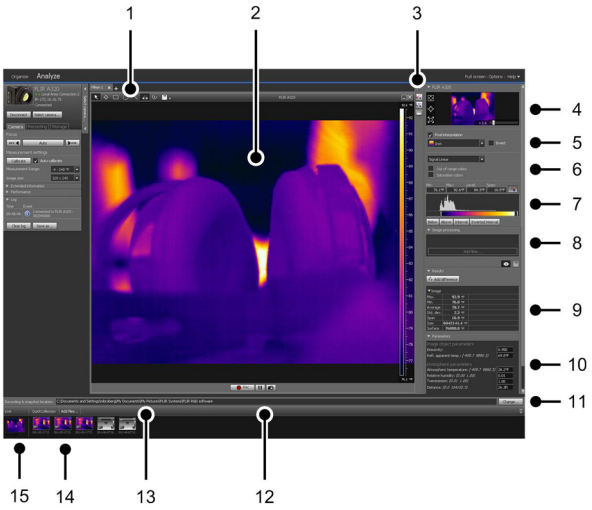
1	Explorer pane. The explorer pane works in the same way as Microsoft Windows Explorer. You can expand folders, select external drives, etc.
2	File pane.
3	Buttons to change the file view: ■ **Thumbnails.** ■ **Details.** ■ **Filmstrip.**
4	■ File information pane: Information about the selected file, such as its filename, when it was created, and when it was modified. ■ Camera information pane: Information about the camera from which the selected file originates, such as the camera model, its lens, and its serial number. ■ Parameters pane: Object parameters and their current values for the selected file.

8.2 *Analyze tab*

8.2.1 Analyze tab (overview)

Figure

T630401;a4



Explanation

This table explains the figure above:

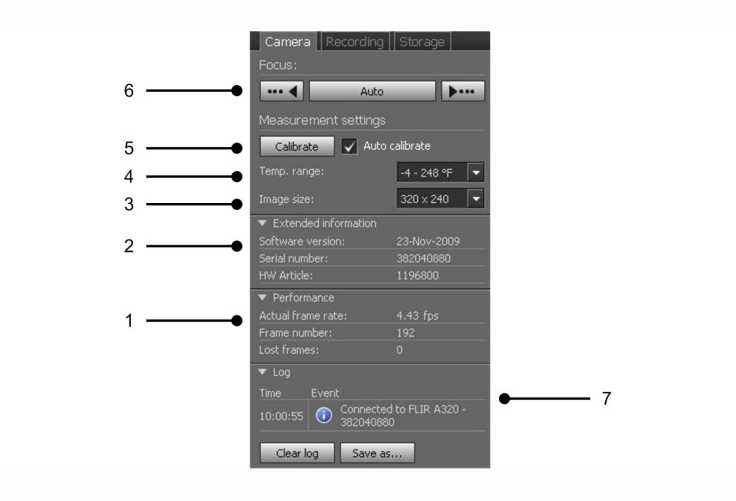
1	Measurement toolbar. You use this toolbar to add measurement tools to the image, such as spots, lines, and areas.
2	Image window. This image window is where the image from the currently connected camera, or an image file on your computer or network, is displayed.
3	Buttons to add more image window tabs, plot tabs, and profile tabs, and to select the different tabs.
4	**Zoom andPan** pane. You use the **Zoom and Pan** pane to change the zoom factor, and to pan over images.
5	Controls to to enable and/or select one or more of the following: ▪ Pixel interpolation. ▪ Color palette.

6	**Image enhancements pane**. You use the **Image enhancements** pane to enable and/or select one or more of the following: ▪ **Signal Linear** ▪ **Histogram equalization** ▪ **Temperature Linear**
7	**Scale** pane. You use the **Scale** pane to carry out various adjustments on the image. You can choose between several different adjustment methods, and also assign a color to display portions of the image that lie above or below a set temperature level, or inside a set temperature interval.
8	**Image processing** pane. You use the **Image processing** pane to enable and/or select one or more of the following filters: ▪ **Subtraction**. ▪ **Sliding Subtraction**. ▪ **Weighted average**. In FLIR ResearchIR Max you can also enable a range of image processing filters. For more information about these filters, see section 14 – Image processing filters on page 49.
9	**Results** pane. The resultspane displays the results of any measurement tools that you have laid out in the image. This pane also displays the position of each measurement tool, and controls which way you want to plot temperatures in a plot window.
10	This area displays parameters, such as focus, calibration, measurement range, and image size.
11	Button to change the recording snapshot location.
12	Recording toolbar.
13	Recording snapshot location.
14	Quick Collectionpane (also visible on the **Organize** tab). The Quick Collection pane is a collection of shortcuts to the original files. Hence, the Quick Collection can contain files that reside in different locations on your computer or network.
15	Live source control (also visible on the **Organize** tab). The live source control displays a thumbnail of the image from the currently connected camera, together with the camera name.

8.2.2 Analyze tab > Camera tab

Figure

T630402;a3



Explanation

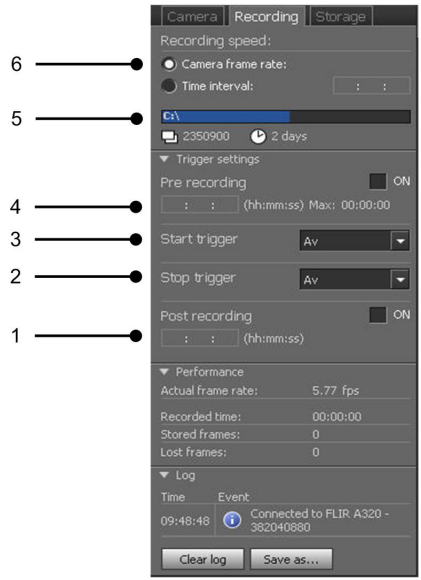
This table explains the figure above:

1	**Performance** area. The **Performance** area displays the performance of the currently connected camera. Here, you can review the frame rate, recording time, number of stored and lost image frames, etc.
2	**Extended information** area. The **Extended information** displays information about the currently connected camera such as: ▪ Software version. ▪ Serial number. ▪ HW Article.
3	Image size (160 × 120, 320, 240, etc.)
4	Temperature range.
5	Buttons to calibrate the camera.
6	Buttons to focus and autofocus the camera.
7	**Log** area. The logarea displays all events that occur during the time a camera is connected. You can clear the log, and also export the log data as an HTML or XML file.

8.2.3 Analyze tab > Recording tab

Figure

T630403;a4



Explanation

This table explains the figure above:

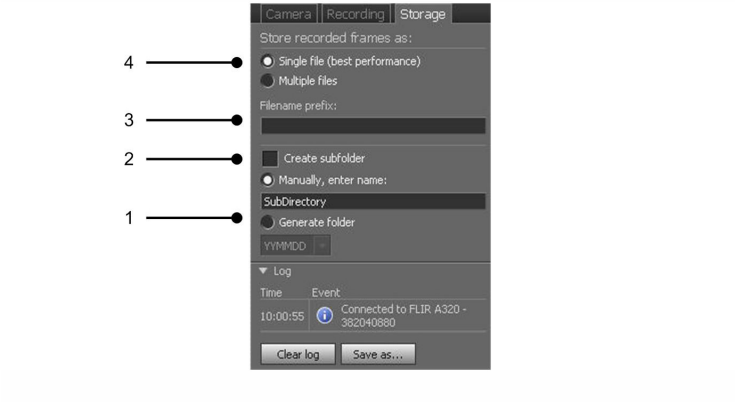
1	(FLIR ResearchIR Max only) Post-recording settings. A postrecording is a defined number of image frames that are stored after the recording that an event has triggered. The image frames in a postrecording are retrieved from a looping image buffer. In many situations, a postrecording is necessary in order to carry out a successful analysis of the recorded event. A postrecording also provides a full history of the event that triggers the stop of the recording. You set the prerecording as a time interval.
2	Controls to set the stop trigger: **Off**, **Date & Time**, **Duration**, **Conditional**. **Conditional** can use **Image.Min.**, **Image.Average.**, **Image.StdDev.**, **Image.Span.**, **Image.Sum.** Similar conditions apply to any measurement tools laid out in the image.

3	Controls to set the start trigger: **Off**, **Date & Time**, **Conditional**. **Conditional** can use **Image.Min.**, **Image.Average.**, **Image.StdDev.**, **Image.Span.**, **Image.Sum.** Similar conditions apply to any measurement tools laid out in the image..
4	(FLIR ResearchIR Max only) Pre-recording settings. A prerecording is a defined number of image frames that are stored before the actual event that triggers the recording takes place. The image frames in a prerecording are retrieved from a looping image buffer. In many situations, a prerecording is necessary in order to carry out a successful analysis of the recorded event. A prerecording also provides a full history of the event that triggers the start of the recording. You set the prerecording as a time interval.
5	▪ The horizontal bar indicates the available space on your hard disk drive that you can use to save image frames. ▪ The left icon indicates the same information, but as the number of image frames, assuming that no settings are changed. ▪ The right icon indicates the same information, but in minutes, assuming that no settings are changed.
6	Controls to set the recording speed: ▪ According to the camera frame rate. ▪ According to the time interval between saved image frames.

8.2.4 Analyze tab > Storage tab

Figure

T630404;a3



Explanation

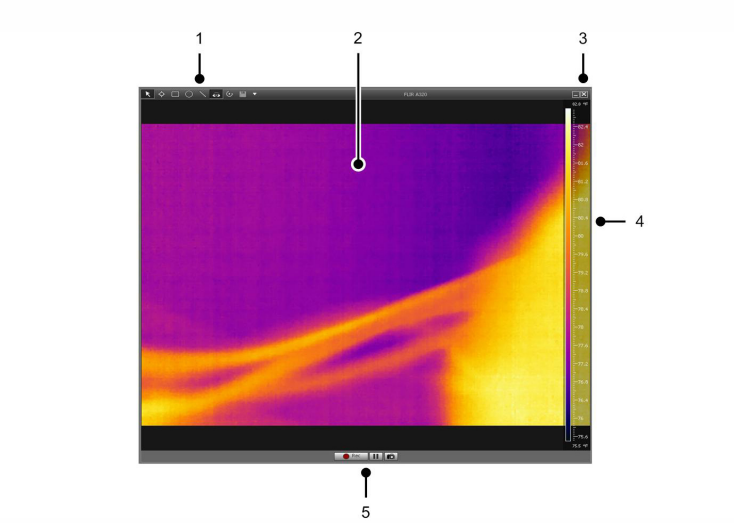
This table explains the figure above:

1	**Generate folder** check box. If you select this check box, the program automatically generates subfolders according to various date formats, assuming that **Create subfolder** is selected in 2 below.
2	**Create subfolder** check box. If you select this check box, you can choose to manually create a subfolder.
3	**Filename prefix** text box. Here, you can define an alphanumerical prefix that will be added to all recorded filenames.
4	Option buttons that control how the recorded files will be saved: ▪ **Single file** (*.seq). ▪ **Multiple files** (*.fff). ▪ *.ptw files (only supported for cameras from FLIR Advanced Thermal Systems).

8.3 Image window

Figure

T630405;a2



Explanation

This table explains the figure above:

1	Measurement toolbar.
2	Image window.
3	Close/minimize button.
4	Temperature scale.
5	Recording toolbar.

NOTE

You can go between a normal window and full screen by pressing F11.

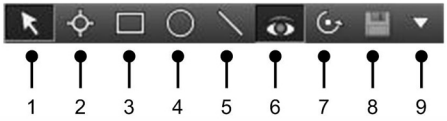
Right-clicking the image window lets you do the following:

- Change the palette.
- Hide the overlay.
- Create a plot.
- Export (as pictures or data).
- Copy (as pictures or data).

8.3.1 Image window > Measurement toolbar

Figure

T630406;a5



Explanation

This table explains the figure above:

1	Select tool. You use this tool when you want to move spots, areas, and lines within an image.
2	Spotmeter tool. You use this tool to create a spotmeter that you can put anywhere on the image. The spotmeter and the temperature it displays will be stored with the image when you save it. To move the spotmeter, use the Select tool to select the spotmeter tool, then click-drag the tool.
3	Area tool. You use this tool to click-and-drag within the image to create an area. The minimum and maximum temperatures in the area will be displayed in the measurement results table. To move the area, use the Select tool to select the area tool, then click-drag the tool.
4	Circle/ellipse tool. You use this tool to click-and-drag within the image to create a circle. The minimum and maximum temperatures in the area will be displayed in the measurement results table. To move the circle, use the Select tool to select the circle tool, then click-drag the tool.
5	Line/polyline tool. You use this tool to create a line within the image. The minimum and maximum temperatures along the line will be displayed in the measurement results table. To move the line, use the Select tool to select the line tool, then click-drag the tool.
6	Show/hide overlay graphics tool. You use this tool to display and hide the overlay graphics that are associated with the image from the infrared camera.

7	Tool to rotate the image and measurement tools.
8/9	Button and drop-down menu to save the image as a picture file or to export it as a *.csv plain-text data file.

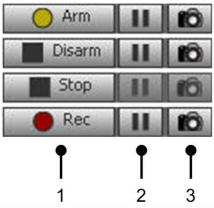
8.3.2 Image window > Sequence recording toolbar

NOTE

- Row 1 shows what the toolbar looks like before the recording has started and before the trigger has been armed.
- Row 2 shows what the toolbar looks like before the recording has started and after the trigger has been armed.
- Row 3 shows what the toolbar looks like during recording.
- Row 4 shows what the toolbar looks like before the recording has started and during pause.

Figure

T630407;a2



Explanation

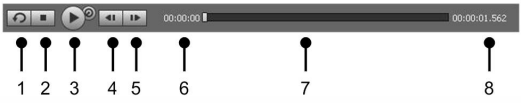
This table explains the figure above.

1	**Arm**/**Disarm**/**Stop**/**Rec** button.
2	Pause button.
3	Button to save a single snapshot as a *.jpg file (or a *ptw file for cameras from FLIR Advanced Thermal Systems).

8.3.3 Image window > Sequence playback toolbar

Figure

T630423;a2



Explanation

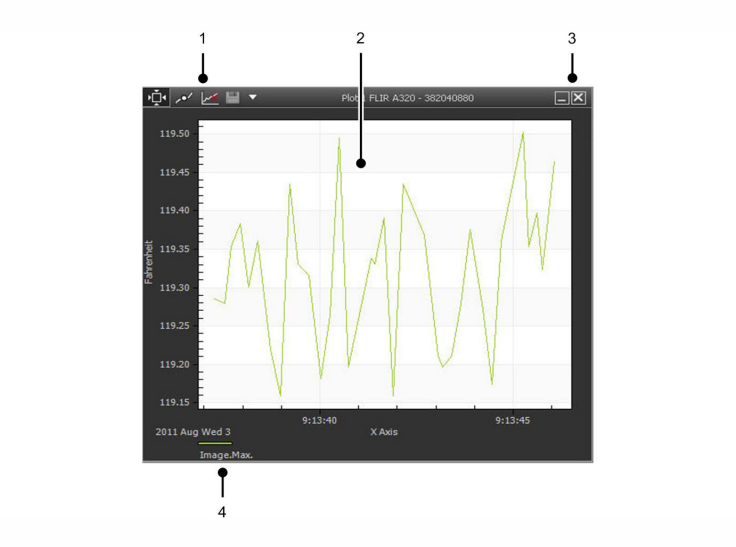
This table explains the figure above.

1	Button to loop the playback.
2	Stop button.
3	Play/pause button.
4	Button to go back one image frame at a time.
5	Button to go forward one image frame at a time.
6	Duration counter.
7	Slider to move through the sequence file.
8	Duration counter.

8.4 Plot window

Figure

T630408;a2



Explanation

This table explains the figure above:

1	Plot toolbar.
2	Plot.
3	Close/Minimize button.
4	Legend.

NOTE

Right-clicking the plot lets you do the following:

- Show the whole plot.
- Show the grid.
- Show the legend.
- Export (as pictures or data).
- Copy (as pictures or data).
- Delete the plot.

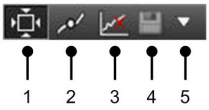
8.4.1 Plot window > Plot toolbar

General

Different parts of the plot toolbar are displayed in live and playback modes.

Figure

T630422;a3



Explanation

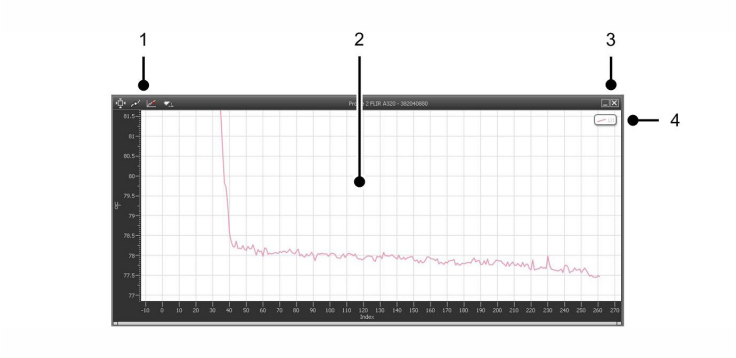
This table explains the figure above:

1	Button to display markers along the plot line. When you hold the cursor over a marker, the temperature is displayed.
2	Button to display a cursor along the plot line.
3	Button to clear the plot window.
4	Button to change the background color.
5	Button to show the whole plot.
6	Button to save the plot in *.plot file format.
7	Button to access file tools: ▪ **Open.** ▪ **Save.** ▪ **Save as.** ▪ **Export.** ▪ **Copy.**

8.5 Profile window

Figure

T638292;a2



Explanation

This table explains the figure above:

1	Profile toolbar.
2	Profile.
3	Close/Minimize button.
4	Legend.

NOTE

Right-clicking the profile lets you do the following:

- Show the whole profile.
- Show the grid.
- Show the legend.
- Export (as pictures or data).
- Copy (as pictures or data).
- Delete the profile.

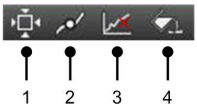
8.5.1 Profile window > Profile toolbar

General

Different parts of the profile toolbar are displayed in live and playback modes.

Figure

T638297;a2



Explanation

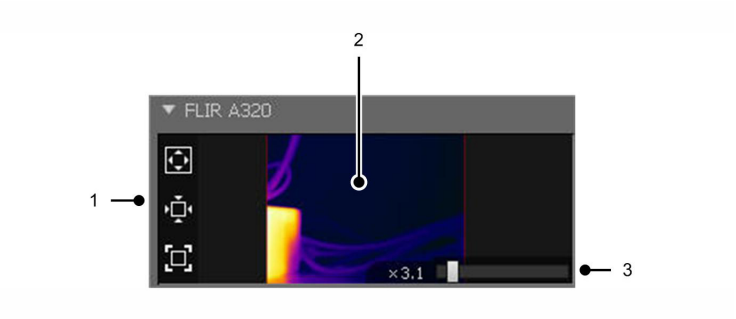
This table explains the figure above:

1	Button to display markers along the profile line. When you hold the cursor over a marker, the temperature is displayed.
2	Button to clear the profile window.
3	Button to change the background color.
4	Button to show the whole profile.
5	Button to copy the image.
6	Button to access file tools: ▪ **Export.** ▪ **Copy.**

8.6 Zoom and Pan pane

Figure

T630410;a2



Explanation

This table explains the figure above:

1	Toolbar buttons (from top to bottom): ▪ Zoom to fill the window with an image. ▪ Zoom to fit the image in the window. ▪ Zoom to the actual image size (1:1).
2	Preview window. If you have zoomed into an image, the excluded image area will be displayed in a lighter shade (see the image). You can then move the zoomed-in area over the image using the cursor.
3	Zoom factor, and the slider to change the zoom factor.

8.7 *Scale pane*

General

The scale pane lets you set maximum and minimum temperatures, create isotherms, and adjust the image in various ways.

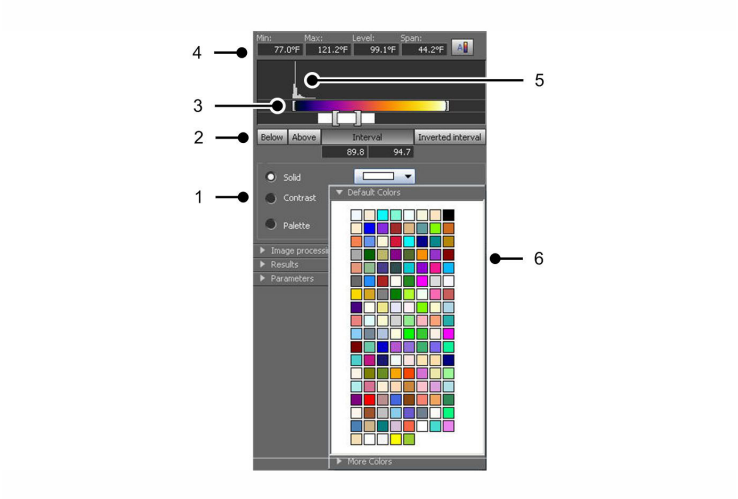
About isotherms

An isotherm is a function highlighting those parts of an image that fall above, below, or between one or more temperature intervals. In FLIR R&D software suite 3.1, you can set four different types of isotherm:

- **Interval**: Assign a color to temperatures between two set temperature levels.
- **Inverted interval**: Assign a color to temperatures between two set temperature levels, but color inverted.
- **Above**: Assign a color to temperatures above a set temperature level.
- **Below**: Assign a color to temperatures below a set temperature level.

Figure

T630411;a8



Explanation

This table explains the figure above:

1	Types of isotherm colorization: ■ **Solid**, i.e., a solid color will be applied to the defined temperature span. ■ **Contrast**, i.e., a slightly transparent contrast color will be applied to the defined temperature span. ■ **Palette**, i.e., a transparent palette color will be applied to the defined temperature span.

2	Buttons to change the isotherm type (left to right): ■ Button to assign a color to temperatures below a set temperature level. ■ Button to assign a color to temperatures above a set temperature level. ■ Button to assign a color to temperatures between two set temperature levels. ■ Button to assign a color to temperatures between two set temperature levels, but color inverted.
3	Sliders to do the following: ■ Automatically adjust the image for the best brightness and contrast. ■ Change the level (by dragging the slider). ■ Change the span (by SHIFT-dragging the sliders). The bottom markers indicate the area in the temperature scale where the defined isotherm color is displayed.
4	Text boxes to enter the following: ■ **Min**: Set specific minimum temperature levels in the image. ■ **Max**: Set specific maximum temperature levels in the image. ■ **Level**: Set the temperature level of the image. ■ **Span**: Set the temperature span of the image. **Note:** These are four mutually exclusive methods to change the same temperature values.
5	Graphical representation of the temperature distribution.
6	Color chart to select a custom color.

8.8 *Results pane*

General

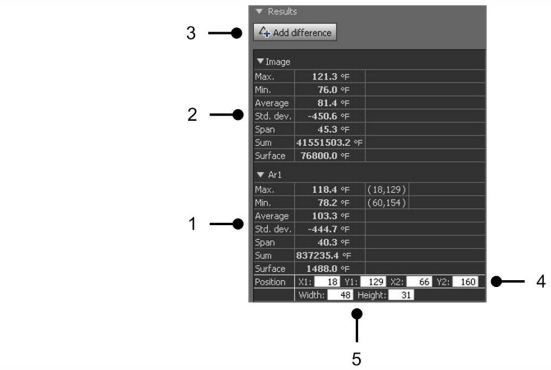
The results pane displays results from the measurement tools laid out in the image.

NOTE

The figure below shows the results pane when an area has been laid out in the image or sequence file. The results pane will look different when other measurement tools are laid out.

Figure

T638293;a2



Explanation

This table explains the figure above:

1	Measurement results for the area.
2	General temperature information for the whole image.
3	Button to create a difference calculation (requires at least two measurement tools laid out in the image).
4	X and Y positions of the measurement tool.
5	Width and height of the measurement tool.

9 Recording sequence files

9.1 How to set the recording speed

General

Before you start your recording, you need to set the recording speed. The recording speed is the number of frames per second that are saved in the file when you record a sequence.

You can set the recording speed using two different methods:

- Changing the camera frame rate.
- Specifying a time interval between saved image frames.

Procedure

Follow this procedure:

1	Go to **Analyze** > **Recording**.
2	Do one of the following: ■ Select a new frame rate in the drop-down menu. ■ Specify a time interval between saved image frames. In a few seconds you will see how the **Actual frame rate** under **Performance** will be updated to match the changed frame rate. Note that discrepancies may occur for higher frame rates, due to some cameras not being able to deliver those frame rates.

NOTE

For an explanation of screen elements, see section 8 – Overview of screen elements on page 18.

9.2 How to set a start trigger

General

A start trigger sets the condition that starts the recording of an event, once the value of the condition is met. In FLIR R&D software suite 3.1 you can use the following types of start trigger:

- **Manual**: The recording is started manually.
- **Date & Time**: The recording is started at a set date and time.
- **Conditional**: The recording is started when a measurement value in the image falls above or below a set value. This assumes that you have laid out at least one measurement tool in the image.

Procedure

Follow this procedure:

1	Go to **Analyze** > **Recording**.
2	In the **Start Trigger** drop-down menu, select one of the following: ▪ **Off.** ▪ **Date & Time.** ▪ **Conditional** (can also use **Image.Min.**, **Image.Average.**, **Image.StdDev.**, **Image.Span.**, **Image.Sum.** Similar conditions apply to any measurement tools laid out in the image.)
3	(When all the start and stop trigger parameters are set.) On the recording toolbar, click **Arm**. This arms the trigger, and the program is now ready to start recording the event once the trigger condition is met.

NOTE

For an explanation of screen elements, see section 8 – Overview of screen elements on page 18.

9.3 How to set a stop trigger

General

A stop trigger sets the condition that stops the recording of an event, once the value of the condition is met. In FLIR R&D software suite 3.1 you can use the following types of stop trigger:

- **Manual**: The recording is stopped manually.
- **Date & Time**: The recording is stopped at a set date and time.
- **Duration**: The recording is stopped after a set time has elapsed since the recording was started.
- **Conditional**: The recording is stopped when a measurement value in the image falls above or below a set value. This assumes that you have laid out at least one measurement tool in the image.

Procedure

Follow this procedure:

1	Go to **Analyze** > **Recording**.
2	In the **Stop Trigger** drop-down menu, select one of the following: ■ **Off**. ■ **Date & Time**. ■ **Duration**. ■ **Conditional** (can also use **Image.Min.**, **Image.Average.**, **Image.StdDev.**, **Image.Span.**, **Image.Sum.** Similar conditions apply to any measurement tools laid out in the image.)
3	(When all the start and stop trigger parameters are set.) On the recording toolbar, click **Arm**. This arms the trigger, and the program is now ready to stop recording the event once the trigger condition is met.

NOTE

For an explanation of screen elements, see section 8 – Overview of screen elements on page 18.

10 Working with plots

General

A temperature plot is a graph that displays how temperature varies relative to time in a sequence file.

NOTE

This procedure assumes that you have connected to a camera and that a live or recorded image is visible in the image window.

Procedure

Follow this procedure:

1	Lay out a measurement tool in the image.
2	Right-click the measurement tool, and select **Plot** and the measurement type that you want to plot (typically the maximum, minimum, or average temperature). A plot will now be displayed.
3	At this stage, you may want to do one of the following: ▪ Copy the plot as a picture and paste it into a technical report, a white paper, etc. ▪ Copy the plot as a *.csv file. ▪ Export the plot as a picture. ▪ Export the plot as data.

NOTE

- For an explanation of screen elements, see section 8 – Overview of screen elements on page 18.
- For an explanation of how to locate files, see section 7.5 – Locating images or sequence files on page 16.
- For an explanation of how to record a sequence file, see section 9 – Recording sequence files on page 39.
- For an explanation of how export images and data, see section 12 – Exporting data on page 44.

11 Working with profiles

General

A profile is as a graph that displays how temperature varies relative to a line in an image.

NOTE

This procedure assumes that you have connected to a camera and that a live or recorded image is visible in the image window.

Procedure

Follow this procedure:

1	Lay out a measurement line in an image.
2	Right-click the measurement tool, and select **Profile** to create a new profile tab. A profile will now be displayed.
3	At this stage, you may want to do one of the following: ■ Copy the plot as a picture and paste it into a technical report, a white paper, etc. ■ Copy the plot as a *.csv file. ■ Export the plot as a picture. ■ Export the plot as data.

NOTE

- For an explanation of screen elements, see section 8 – Overview of screen elements on page 18.
- For an explanation of how to locate files, see section 7.5 – Locating images or sequence files on page 16.
- For an explanation of how to record a sequence file, see section 9 – Recording sequence files on page 39.
- For an explanation of how export images and data, see section 12 – Exporting data on page 44.

12 Exporting data

General

You can export image, plot, and profile data in various ways. This section describes how.

Exporting image data

Do one of the following:

- Right-click an image and select **Export** > **IR Bitmap**. This will export the current image as a *.bmp file.
- Right-click an image and select **Export** > **Sequence data as CSV**. This will export the current image as a *.csv file with an array of temperature values corresponding to the pixels.
- Right-click an image and select **Export** > **AVI Video file**. This will export the current image as an *.avi video file.

Exporting plot data

Do one of the following:

- Right-click a plot and select **Export** > **Picture**. This will export the current plot as a *.bmp file.
- Right-click a plot and select **Export** > **Data to *.csv**. This will export the current plot as a *.csv file with the following columns:
  - Date.
  - Time.
  - Milliseconds.
  - Relative time.
  - Average temperature.
- Right-click a plot and select **Export** > **Data to *.tsv**. This will export the current plot as a *.tsv (tab-separated) file with the following columns:
  - Date.
  - Time.
  - Milliseconds.
  - Relative time.
  - Average temperature.

Exporting profile data

Do one of the following:

- Right-click a profile and select **Export** > **Picture**. This will export the current profile as a *.bmp file.
- Right-click a profile and select **Export** > **Data**. This will export the current profile as a *.csv file with the following columns:
  - Index of markers.
  - Temperatures of markers.

Exporting sequence data

Do one of the following:

- Right-click an image and select **Export** > **IR Bitmap**. This will export the current image as a *.bmp file.

- Right-click an image and select **Export** > **Sequence data as CSV**. This will export the current image as a *.csv file with an array of temperature values corresponding to the pixels.
- Right-click an image and select **Export** > **AVI Video file**. This will export the current image as an *.avi video file.

13 Changing settings

13.1 Changing the program settings

General

You can change a variety of program settings that define the output data, temperature units, language, etc.

Procedure

Follow this procedure:

1	On the main menu bar, click **Options**.

2	Do one of the following:
	▪ To change the units, click the **Units** tab and do one of the following:
	  ▪ To change the output data, select **Raw count**, **Object signal**, or **Temperature**.
	  ▪ To change the temperature unit, select **Celsius**, **Fahrenheit**, or **Kelvin**.
	▪ To change the connection behavior, click the **Application** tab, and select **Auto-connect to camera** or **Disable warning message before save**.
	▪ To change the language, click the **Language** tab, and select a new language.

Explanation

- **Raw count**: The pixel value as delivered by the camera on the digital interface or as saved in radiometric image files. No correction for object parameters is included. Depending on the camera model, drift compensation may also not be included.
- **Object signal**: A calibrated value proportional to the radiation from the object. This is the detector signal corrected for drift, gain, and offset, including compensation for object parameters. The correct setting of object parameters (reflected apparent temperature, emissivity, object distance, relative humidity, and atmospheric temperature) is assumed.
- **Temperature**: The blackbody temperature of the object when the calibration algorithm based on Planck's law is applied to the object signal.

13.2 Changing object parameters

13.2.1 Changing object parameters globally

General

For accurate measurements, you must set the object parameters. This procedure describes how to change the object parameters globally.

Atmospheric parameters group

- **Atmospheric temperature**: The temperature of the air between the camera and the object of interest.
- **Relative humidity**: The relative humidity of the air between the camera and the object of interest.
- **Transmission**: The computed or fixed transmission through the atmosphere.

External optics group

- **Temperature**: The temperature of any protective windows, etc., that are set up between the camera and the object of interest. If no protective window or protective shield is used, this value is irrelevant.
- **Transmission**: The optical transmission of any protective windows, etc., that are set up between the camera and the object of interest.

Image object parameters group

- **Emissivity**: How much radiation an object emits, compared with the radiation of a theoretical reference object of the same temperature (called a 'blackbody'). The opposite of emissivity is reflectivity. The emissivity determines how much of the radiation originates from the object as opposed to being reflected by it.
- **Distance**: The distance between the camera and the object of interest.
- **Reflected apparent temperature**: Used when compensating for the radiation from the surroundings reflected by the object into the camera. This property of the object is called reflectivity.

Procedure

Follow this procedure:

1	Go to the **Parameters** pane.
2	Put the cursor in the white text box to the right of the parameter that you want to change.
3	Type the new value and press the RETURN key.

Related topics

For in-depth information about parameters, and how to correctly set the emissivity and reflected apparent temperature, see section 17 – Thermographic measurement techniques on page 60.

13.2.2 Changing object parameters locally

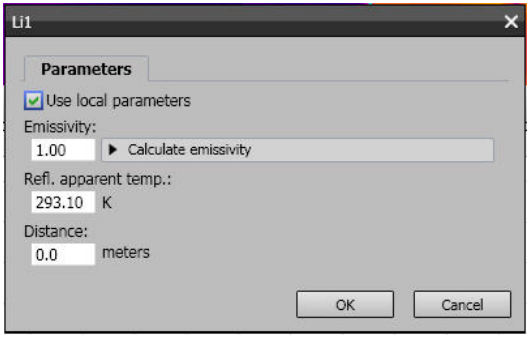
General

When you change the object parameters, all the object parameters for the whole image are changed.

However, in some situations you want to change an object parameter for one measurement tool only. The reason for this may be that the measurement tool is in front of a significantly more reflective surface than other surfaces in the image, or over an object that is further away than the rest of the objects in the image, and so on.

Procedure

Follow this procedure:

1	Place at least one measurement tool in the image.
2	Right-click the tool and select **Parameters**. This will display the following dialog box. T638028;a3 
3	Select **Use local parameters**.
4	Do one of the following: ▪ Let the program calculate the emissivity. This requires knowledge of the temperature of the object in question. ▪ Enter a known value for the reflected apparent temperature. ▪ Enter a known value for the distance to the object.

NOTE

- You can also change an object parameter locally by right-clicking the measurement result in the results pane.
- Using the emissivity calculator requires that **Data output** is set to Kelvin, Celsius, or Fahrenheit under **Options**.

Related topics

For in-depth information about parameters, and how to correctly set the emissivity and reflected apparent temperature, see section 17 – Thermographic measurement techniques on page 60.

14 Image processing filters

In FLIR ResearchIR Max, you can enable the following image processing filters.

Category	Filter	Description
Highpass Filtering	Canny	Edge detection operator named after John F. Canny. A multi-stage algorithm, including noise reduction and gradient detection, where the thresholds determine the allowed interval of intensity gradients. Default threshold values are approximations.
	Laplacian	Highpass filtering with a second derivative Laplacian operator.
	Sobel	Highpass filtering with a first derivative, horizontal or vertical, Sobel operator.
	Sobel Cross	Highpass filtering with a second cross derivative Sobel operator.
Lowpass Filtering	Gaussian	Lowpass filtering with a Gaussian filter kernel. Sigma specifies the shape of the Gaussian, and thereby the amount of smoothening.
	Window Average	Lowpass filtering by averaging the pixel values in a square window.
Noise reduction	Median Filter	Replaces each pixel with the median pixel value from a surrounding window.
	Wiener Filter	Noise reduction filter based on pixel value statistics, named after Norbert Wiener. The parameter Noise specifies the estimated noise level in the image (range [0, 1]).
Pixel Operators	Exponential	The exponential of each pixel value (e to the pixel value).
	Gain	Multiplies each pixel by a constant gain. Both positive and negative gain values are allowed.

Category	Filter	Description
	Invert	Pixel values are inverted within the interval spanned by the input image.
	Natural Logarithm	The natural logarithm of each pixel value.
	Offset	Adds a constant offset to each pixel. Both positive and negative offset values are allowed.
	Power	Each pixel value raised to the power of Pow.
	Square root	The square root of each pixel value.
Temporal Filtering	Max - Continuous	Each pixel is given the maximum pixel value found within previous frames. All frames from the beginning of the sequence, or from the last Reset, are included.
	Max - Frame interval	Each pixel is given the maximum pixel value found within a limited set of previous frames. Number of frames is specified in Delay.
	Min - Continuous	Each pixel is given the minimum pixel value found within previous frames. All frames from the beginning of the sequence, or from the last Reset, are included.
	Min - Frame interval	Each pixel is given the minimum pixel value found within a limited set of previous frames. Number of frames is specified in Delay.
	Pixel Average	Each pixel is given the average pixel value of a number of previous frames. Number of frames is specified in Depth.
	Fixed Subtraction	Derives the relative or absolute difference between the current frame and a fixed reference frame. For the relative difference, the reference frame is subtracted from the current frame.

Category	Filter	Description
	Sliding Subtraction	Derives the relative or absolute difference between the current frame and a previous frame, specified by a frame delay. For the relative difference, the reference frame is subtracted from the current frame.
	Weighted Average	Each pixel is given a weighted average of a number of previous frames. Number of frames is specified in Depth. The weight curve can be either Gaussian, where the peak is centered over the frame window, or Exponential, where the current frame has the highest weight, and the weight curve is decreasing towards 0 when approaching the specified Depth.

15 About FLIR Systems

FLIR Systems was established in 1978 to pioneer the development of high-performance infrared imaging systems, and is the world leader in the design, manufacture, and marketing of thermal imaging systems for a wide variety of commercial, industrial, and government applications. Today, FLIR Systems embraces five major companies with outstanding achievements in infrared technology since 1958—the Swedish AGEMA Infrared Systems (formerly AGA Infrared Systems), the three United States companies Indigo Systems, FSI, and Inframetrics, and the French company Cedip. In November 2007, Extech Instruments was acquired by FLIR Systems.

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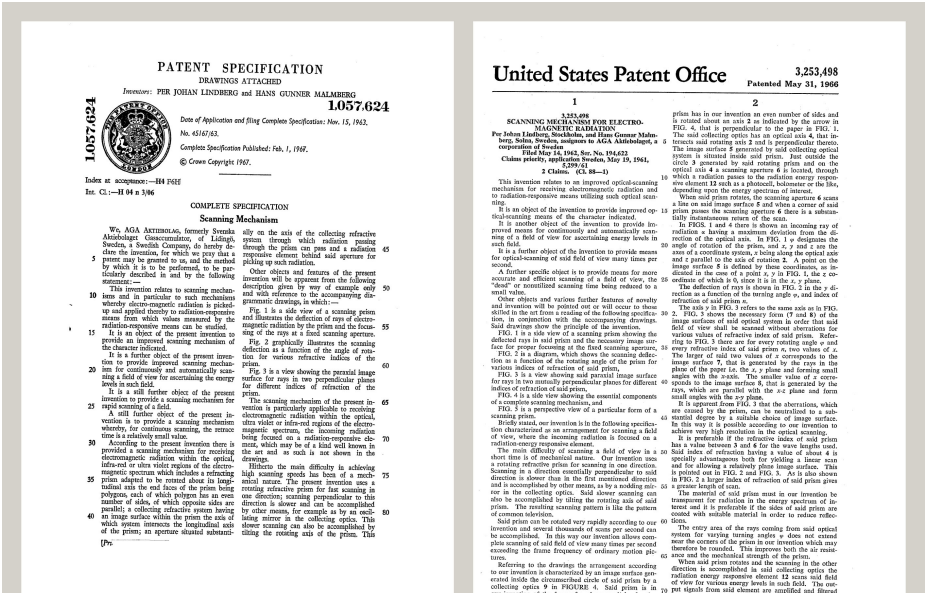

PATENT SPECIFICATION

DRAWINGS ATTACHED

Inventors: PER JOHAN LINDBERG and HANS GUNNER MALMBERG

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No. 45167/63.

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1057.624

Index at acceptance:—H04 P6H

Int. Cl.:—H 04 n 3/06

COMPLETE SPECIFICATION

Scanning Mechanism

We, AGA AKTIEBOLAG, formerly Svenska Aktiebolaget Gasaccumulator, of Lidingö, Sweden, a Swedish Company, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to scanning mechanisms and in particular to such mechanisms whereby electro-magnetic radiation is picked-up and applied thereby to radiation-responsive means from which videos measured by the radiation-responsive means can be studied.

It is an object of the present invention to provide an improved scanning mechanism of the character indicated.

It is a further object of the present invention to provide improved scanning mechanism for continuously and automatically scanning a field of view for ascertaining the energy levels in such field.

It is a still further object of the present invention to provide a scanning mechanism for rapid scanning of a field.

A still further object of the present invention is to provide a scanning mechanism whereby, for continuous scanning, the retrace time is a relatively small value.

According to the present invention there is provided a scanning mechanism for receiving electromagnetic radiation within the optical, infra-red or ultra violet regions of the electromagnetic spectrum which includes a refracting prism adapted to be rotated about its longitudinal axis the end faces of the prism being polygons, each of which polygon has an even number of sides, of which opposite sides are parallel; a collecting refractive system having an image surface within the prism the axis of which system intersects the longitudinal axis of the prism; an aperture situated substantially on the axis of the collecting refractive system through which radiation passing through the prism can pass and a radiation responsive element behind said aperture for picking up such radiation.

Other objects and features of the present invention will be apparent from the following description given by way of example only and with reference to the accompanying diagrammatic drawings, in which:—

Fig. 1 is a side view of a scanning prism and illustrates the deflection of rays of electromagnetic radiation by the prism and the focusing of the rays at a fixed scanning aperture.

Fig. 2 graphically illustrates the scanning deflection as a function of the angle of rotation for various refractive indices of the prism.

Fig. 3 is a view showing the parazial image surface for rays in two perpendicular planes for different indices of refraction of the prism.

The scanning mechanism of the present invention is particularly applicable to receiving electromagnetic radiation within the optical, ultra violet or infra-red regions of the electromagnetic spectrum, the incoming radiation being focused on a radiation-responsive element, which may be of a kind well known in the art and as such is not shown in the drawings.

Hitherto the main difficulty in achieving high scanning speeds has been of a mechanical nature. The present invention uses a rotating refractive prism for fast scanning in one direction; scanning perpendicular to this direction is slower and can be accomplished by other means, for example as by an oscillating mirror in the collecting optics. This slower scanning can also be accomplished by tilting the rotating axis of the prism. This

[Pre

United States Patent Office 3,253,498 Patented May 31, 1966

1 2

3,253,498
SCANNING MECHANISM FOR ELECTRO-MAGNETIC RADIATION
Per Johan Lindberg, Stockholm, and Hans Gunnar Malmberg, Solna, Sweden, assignors to AGA Aktiebolaget, a corporation of Sweden
Filed May 14, 1963, Ser. No. 194,622
Claims priority, application Sweden, May 19, 1961, 5,299/61
2 Claims. (Cl. 88—1)

This invention relates to an improved optical-scanning mechanism for receiving electromagnetic radiation and to radiation-responsive means utilizing such optical scanning.

It is an object of the invention to provide improved optical-scanning means of the character indicated.

It is another object of the invention to provide improved means for continuously and automatically scanning of a field of view for ascertaining energy levels in such field.

It is a further object of the invention to provide means for optical-scanning of said field of view many times per second.

A further specific object is to provide means for more accurate and efficient scanning of a field of view, the "dead" or nonutilized scanning time being reduced to a small value.

Other objects and various further features of novelty and invention will be pointed out or will occur to those skilled in the art from a reading of the following specification, in combination with the accompanying drawings. Said drawings show the principle of the invention.

FIG. 1 is a side view of a scanning prism showing the deflected rays in said prism and the necessary image surface for proper focussing at the fixed scanning aperture, 35

FIG. 2 is a diagram, which shows the scanning deflection as a function of the rotating angle of the prism for various indices of refraction of said prism,

FIG. 3 is a view showing said parazial image surface for rays in two mutually perpendicular planes for different indices of refraction of said prism,

FIG. 4 is a side view showing the essential components of a complete scanning mechanism, and

FIG. 5 is a perspective view of a particular form of a scanning prism.

Briefly stated, our invention is in the following specification characterized as a mechanism for scanning a field of view, where the incoming radiation is focused on a radiation-responsive element.

The main difficulty of scanning a field of view in a short time is of mechanical nature. Our invention uses a rotating refractive prism for scanning in one direction. Scanning in a direction substantially perpendicular to said direction is slower than the first mentioned direction and is accomplished by other means, as by a nodding mirror in the collecting optics. Said slower scanning can also be accomplished by tilting the rotating axis of said prism. The resulting scanning pattern is like the pattern of common television.

Said prism can be rotated very rapidly according to our invention and several thousands of scans per second can be accomplished. In this way our invention allows complete scanning of said field of view many times per second exceeding the frame frequency of ordinary motion pictures.

Referring to the drawings the arrangement according to our invention is characterized by an image surface generated inside the circumscribed circle of said prism by a collecting optics 9 in FIGURE 4. Said prism is in our invention of the form of a plane parallel refractive prism, which is in one case 3 shown in FIG. 1. Said prism has in our invention an even number of sides and is rotated about an axis 2 as indicated by the arrow in FIG. 4, that is perpendicular to the paper in FIG. 1. The said collecting optics has an optical axis 4, that intersects said rotating axis 2 and is perpendicular thereto. The image surface 5 generated by said collecting optical system is situated inside said prism. Just outside the circle 3 generated by said rotating prism and on the optical axis 4 a scanning aperture 6 is located, through which a radiation passes to the radiation energy responsive element 12 such as a photocell, bolometer or the like, depending upon the energy spectrum of interest.

When said prism rotates, the scanning aperture 6 scans a line on said image surface 5 and when a corner of said prism passes the scanning aperture 6 there is a substantially instantaneous return of the scan.

In FIGS. 1 and 4 there is shown an incoming ray of radiation 8 having a maximum deviation from the direction of the optical axis. In FIG. 1 φ designates the angle of rotation of the prism, and x, y and z are the axes of a coordinate system, z being along the optical axis and z parallel to the axis of rotation 2. A point on the image surface 5 is defined by these coordinates, as indicated in the case of a point x, y in FIG. 1, the z coordinate of which is 0, since it is in the x, y plane.

The deflection of rays is shown in FIG. 2 in the y direction as a function of the turning angle φ, and index of refraction of said prism n.

The axis y in FIG. 3 refers to the same axis as in FIG. 2. FIG. 5 shows the necessary faces (7 and 8) of the image surfaces of said optical system in order that said field of view shall be scanned without aberrations for various values of refractive index of said prism. Referring to FIG. 3 there are for every rotating angle φ and every refractive index of said prism n, two values of x. The larger of said two values of x corresponds to the image surface 7, that is generated by the rays in the plane of the paper i.e. the x, y plane and forming small angles with the z-axis. The smaller value of x corresponds to the image surface 8, that is generated by the rays, which are parallel with the x-z plane and form small angles with the x-y plane.

It is apparent from FIG. 3 that the aberrations, which are caused by the prism, can be neutralized to a substantial degree by a suitable choice of image surface. In this way it is possible according to our invention to obtain a substantially aberration free optical scanning.

It is preferable if the refractive index of said prism has a value between 1 and 2 for the wave length used. Said index of refraction having a value of about 4 is specially advantageous both for yielding a larger scan and for allowing a relatively plane image surface. This is pointed out in FIG. 2 and FIG. 3. As is also shown in FIG. 2 a larger index of refraction of said prism gives a greater length of scan.

The material of said prism must in our invention be transparent for radiation in the energy spectrum of interest and it is preferable if the sides of said prism are coated with suitable material in order to reduce reflections.

The entry area of the rays coming from said optical system for varying turning angles φ does not extend near the corners of said prism in our invention which may therefore be rounded. This improves both the air resistance and the mechanical strength of the prism.

When said prism rotates and the scanning in the other direction is accomplished by other scanning optics the radiation energy responsive element 12 from said field of view for various energy levels in said field of view. The output signals from said element are amplified and filtered and may be used to modulate the intensity of a moving spot on a cathode ray tube. The movement of said

Figure 15.1 Patent documents from the early 1960s

The company has sold more than 140,000 infrared cameras worldwide for applications such as predictive maintenance, R & D, non-destructive testing, process control and automation, and machine vision, among many others.

FLIR Systems has three manufacturing plants in the United States (Portland, OR, Boston, MA, Santa Barbara, CA) and one in Sweden (Stockholm). Since 2007 there is also a manufacturing plant in Tallinn, Estonia. Direct sales offices in Belgium, Brazil,

China, France, Germany, Great Britain, Hong Kong, Italy, Japan, Korea, Sweden, and the USA—together with a worldwide network of agents and distributors—support our international customer base.

FLIR Systems is at the forefront of innovation in the infrared camera industry. We anticipate market demand by constantly improving our existing cameras and developing new ones. The company has set milestones in product design and development such as the introduction of the first battery-operated portable camera for industrial inspections, and the first uncooled infrared camera, to mention just two innovations.

10722703;a2

Figure 15.2 LEFT: Thermovision® Model 661 from 1969. The camera weighed approximately 25 kg (55 lb.), the oscilloscope 20 kg (44 lb.), and the tripod 15 kg (33 lb.). The operator also needed a 220 VAC generator set, and a 10 L (2.6 US gallon) jar with liquid nitrogen. To the left of the oscilloscope the Polaroid attachment (6 kg/13 lb.) can be seen. **RIGHT:** FLIR i7 from 2009. Weight: 0.34 kg (0.75 lb.), including the battery.

FLIR Systems manufactures all vital mechanical and electronic components of the camera systems itself. From detector design and manufacturing, to lenses and system electronics, to final testing and calibration, all production steps are carried out and supervised by our own engineers. The in-depth expertise of these infrared specialists ensures the accuracy and reliability of all vital components that are assembled into your infrared camera.

15.1 More than just an infrared camera

At FLIR Systems we recognize that our job is to go beyond just producing the best infrared camera systems. We are committed to enabling all users of our infrared camera systems to work more productively by providing them with the most powerful

camera–software combination. Especially tailored software for predictive maintenance, R & D, and process monitoring is developed in-house. Most software is available in a wide variety of languages.

We support all our infrared cameras with a wide variety of accessories to adapt your equipment to the most demanding infrared applications.

15.2 Sharing our knowledge

Although our cameras are designed to be very user-friendly, there is a lot more to thermography than just knowing how to handle a camera. Therefore, FLIR Systems has founded the Infrared Training Center (ITC), a separate business unit, that provides certified training courses. Attending one of the ITC courses will give you a truly hands-on learning experience.

The staff of the ITC are also there to provide you with any application support you may need in putting infrared theory into practice.

15.3 Supporting our customers

FLIR Systems operates a worldwide service network to keep your camera running at all times. If you discover a problem with your camera, local service centers have all the equipment and expertise to solve it within the shortest possible time. Therefore, there is no need to send your camera to the other side of the world or to talk to someone who does not speak your language.

15.4 A few images from our facilities

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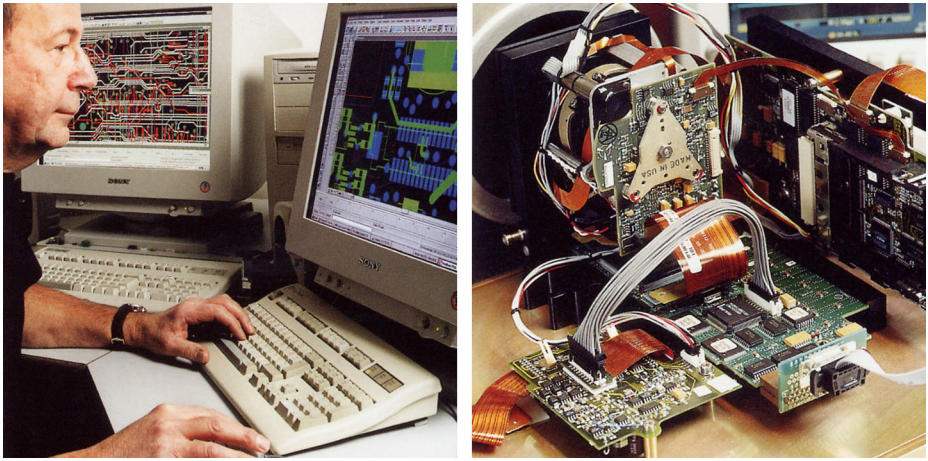


Figure 15.3 LEFT: Development of system electronics; **RIGHT:** Testing of an FPA detector

10401403;a1

Figure 15.4 LEFT: Diamond turning machine; **RIGHT:** Lens polishing

10401503;a1

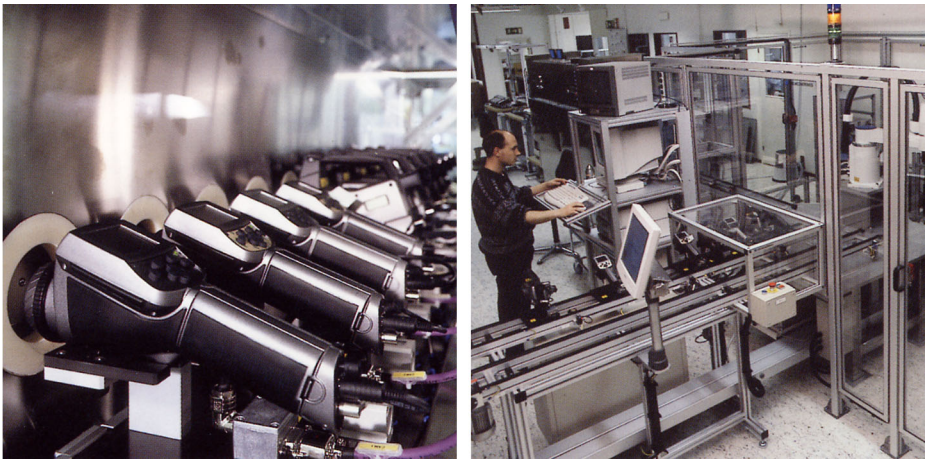


Figure 15.5 LEFT: Testing of infrared cameras in the climatic chamber; **RIGHT:** Robot used for camera testing and calibration

16 Glossary

Term or expression	Explanation
absorption (absorption factor)	The amount of radiation absorbed by an object relative to the received radiation. A number between 0 and 1.
atmosphere	The gases between the object being measured and the camera, normally air.
autoadjust	A function making a camera perform an internal image correction.
autopalette	The IR image is shown with an uneven spread of colors, displaying cold objects as well as hot ones at the same time.
blackbody	Totally non-reflective object. All its radiation is due to its own temperature.
blackbody radiator	An IR radiating equipment with blackbody properties used to calibrate IR cameras.
calculated atmospheric transmission	A transmission value computed from the temperature, the relative humidity of air and the distance to the object.
cavity radiator	A bottle shaped radiator with an absorbing inside, viewed through the bottleneck.
color temperature	The temperature for which the color of a blackbody matches a specific color.
conduction	The process that makes heat diffuse into a material.
continuous adjust	A function that adjusts the image. The function works all the time, continuously adjusting brightness and contrast according to the image content.
convection	Convection is a heat transfer mode where a fluid is brought into motion, either by gravity or another force, thereby transferring heat from one place to another.
dual isotherm	An isotherm with two color bands, instead of one.
emissivity (emissivity factor)	The amount of radiation coming from an object, compared to that of a blackbody. A number between 0 and 1.
emittance	Amount of energy emitted from an object per unit of time and area (W/m^2)
environment	Objects and gases that emit radiation towards the object being measured.
estimated atmospheric transmission	A transmission value, supplied by a user, replacing a calculated one

Term or expression	Explanation
external optics	Extra lenses, filters, heat shields etc. that can be put between the camera and the object being measured.
filter	A material transparent only to some of the infrared wavelengths.
FOV	Field of view: The horizontal angle that can be viewed through an IR lens.
FPA	Focal plane array: A type of IR detector.
graybody	An object that emits a fixed fraction of the amount of energy of a blackbody for each wavelength.
IFOV	Instantaneous field of view: A measure of the geometrical resolution of an IR camera.
image correction (internal or external)	A way of compensating for sensitivity differences in various parts of live images and also of stabilizing the camera.
infrared	Non-visible radiation, having a wavelength from about 2–13 µm.
IR	infrared
isotherm	A function highlighting those parts of an image that fall above, below or between one or more temperature intervals.
isothermal cavity	A bottle-shaped radiator with a uniform temperature viewed through the bottleneck.
Laser LocatIR	An electrically powered light source on the camera that emits laser radiation in a thin, concentrated beam to point at certain parts of the object in front of the camera.
laser pointer	An electrically powered light source on the camera that emits laser radiation in a thin, concentrated beam to point at certain parts of the object in front of the camera.
level	The center value of the temperature scale, usually expressed as a signal value.
manual adjust	A way to adjust the image by manually changing certain parameters.
NETD	Noise equivalent temperature difference. A measure of the image noise level of an IR camera.
noise	Undesired small disturbance in the infrared image
object parameters	A set of values describing the circumstances under which the measurement of an object was made, and the object itself (such as emissivity, reflected apparent temperature, distance etc.)
object signal	A non-calibrated value related to the amount of radiation received by the camera from the object.

Term or expression	Explanation
palette	The set of colors used to display an IR image.
pixel	Stands for *picture element*. One single spot in an image.
radiance	Amount of energy emitted from an object per unit of time, area and angle ($W/m^2/sr$)
radiant power	Amount of energy emitted from an object per unit of time (W)
radiation	The process by which electromagnetic energy, is emitted by an object or a gas.
radiator	A piece of IR radiating equipment.
range	The current overall temperature measurement limitation of an IR camera. Cameras can have several ranges. Expressed as two blackbody temperatures that limit the current calibration.
reference temperature	A temperature which the ordinary measured values can be compared with.
reflection	The amount of radiation reflected by an object relative to the received radiation. A number between 0 and 1.
relative humidity	Relative humidity represents the ratio between the current water vapour mass in the air and the maximum it may contain in saturation conditions.
saturation color	The areas that contain temperatures outside the present level/span settings are colored with the saturation colors. The saturation colors contain an 'overflow' color and an 'underflow' color. There is also a third red saturation color that marks everything saturated by the detector indicating that the range should probably be changed.
span	The interval of the temperature scale, usually expressed as a signal value.
spectral (radiant) emittance	Amount of energy emitted from an object per unit of time, area and wavelength ($W/m^2/\mu m$)
temperature difference, or difference of temperature.	A value which is the result of a subtraction between two temperature values.
temperature range	The current overall temperature measurement limitation of an IR camera. Cameras can have several ranges. Expressed as two blackbody temperatures that limit the current calibration.
temperature scale	The way in which an IR image currently is displayed. Expressed as two temperature values limiting the colors.
thermogram	infrared image

Term or expression	Explanation
transmission (or transmittance) factor	Gases and materials can be more or less transparent. Transmission is the amount of IR radiation passing through them. A number between 0 and 1.
transparent isotherm	An isotherm showing a linear spread of colors, instead of covering the highlighted parts of the image.
visual	Refers to the video mode of a IR camera, as opposed to the normal, thermographic mode. When a camera is in video mode it captures ordinary video images, while thermographic images are captured when the camera is in IR mode.

17 Thermographic measurement techniques

17.1 Introduction

An infrared camera measures and images the emitted infrared radiation from an object. The fact that radiation is a function of object surface temperature makes it possible for the camera to calculate and display this temperature.

However, the radiation measured by the camera does not only depend on the temperature of the object but is also a function of the emissivity. Radiation also originates from the surroundings and is reflected in the object. The radiation from the object and the reflected radiation will also be influenced by the absorption of the atmosphere.

To measure temperature accurately, it is therefore necessary to compensate for the effects of a number of different radiation sources. This is done on-line automatically by the camera. The following object parameters must, however, be supplied for the camera:

- The emissivity of the object
- The reflected apparent temperature
- The distance between the object and the camera
- The relative humidity
- Temperature of the atmosphere

17.2 Emissivity

The most important object parameter to set correctly is the emissivity which, in short, is a measure of how much radiation is emitted from the object, compared to that from a perfect blackbody of the same temperature.

Normally, object materials and surface treatments exhibit emissivity ranging from approximately 0.1 to 0.95. A highly polished (mirror) surface falls below 0.1, while an oxidized or painted surface has a higher emissivity. Oil-based paint, regardless of color in the visible spectrum, has an emissivity over 0.9 in the infrared. Human skin exhibits an emissivity 0.97 to 0.98.

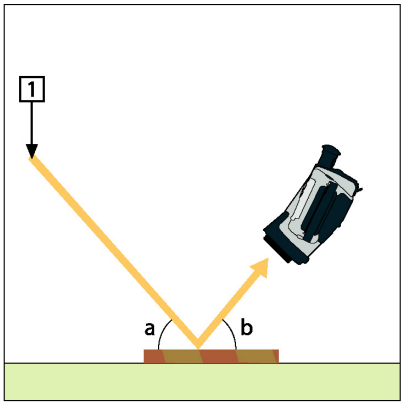
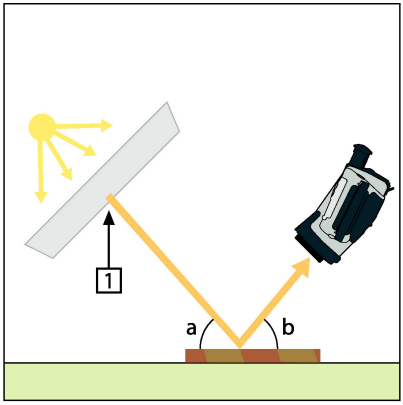
Non-oxidized metals represent an extreme case of perfect opacity and high reflexivity, which does not vary greatly with wavelength. Consequently, the emissivity of metals is low – only increasing with temperature. For non-metals, emissivity tends to be high, and decreases with temperature.

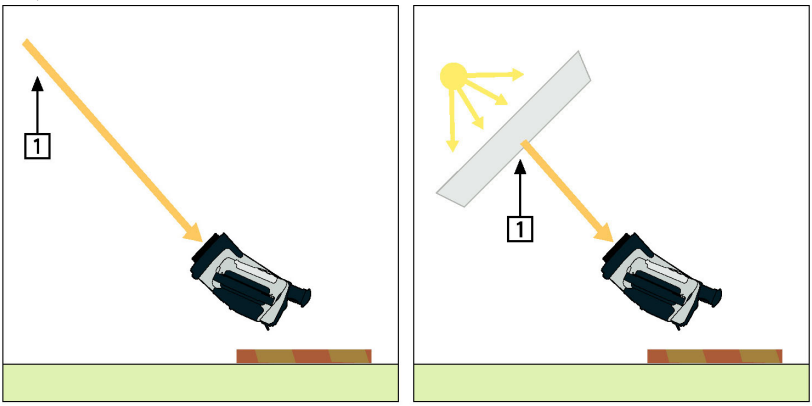
17.2.1 Finding the emissivity of a sample

17.2.1.1 Step 1: Determining reflected apparent temperature

Use one of the following two methods to determine reflected apparent temperature:

17.2.1.1.1 Method 1: Direct method

1	Look for possible reflection sources, considering that the incident angle = reflection angle (a = b). 10588903;a1  **Figure 17.1** 1 = Reflection source
2	If the reflection source is a spot source, modify the source by obstructing it using a piece if cardboard. 10589103;a2  **Figure 17.2** 1 = Reflection source

3	Measure the radiation intensity (= apparent temperature) from the reflecting source using the following settings: ▪ Emissivity: 1.0 ▪ D_{obj}: 0 You can measure the radiation intensity using one of the following two methods: 10589003;a2  **Figure 17.3** 1 = Reflection source

Note: Using a thermocouple to measure reflected apparent temperature is not recommended for two important reasons:

- A thermocouple does not measure radiation intensity
- A thermocouple requires a very good thermal contact to the surface, usually by gluing and covering the sensor by a thermal isolator.

17.2.1.1.2 Method 2: Reflector method

1	Crumble up a large piece of aluminum foil.
2	Uncrumble the aluminum foil and attach it to a piece of cardboard of the same size.
3	Put the piece of cardboard in front of the object you want to measure. Make sure that the side with aluminum foil points to the camera.
4	Set the emissivity to 1.0.

5	Measure the apparent temperature of the aluminum foil and write it down.

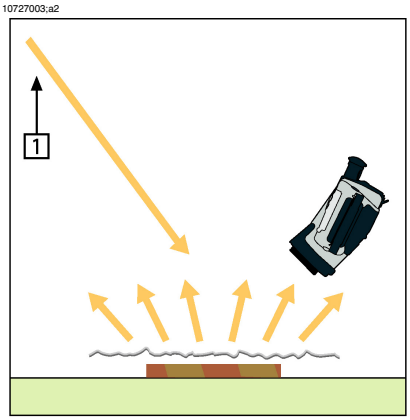


Figure 17.4 Measuring the apparent temperature of the aluminum foil

17.2.1.2 Step 2: Determining the emissivity

1	Select a place to put the sample.
2	Determine and set reflected apparent temperature according to the previous procedure.
3	Put a piece of electrical tape with known high emissivity on the sample.
4	Heat the sample at least 20 K above room temperature. Heating must be reasonably even.
5	Focus and auto-adjust the camera, and freeze the image.
6	Adjust **Level** and **Span** for best image brightness and contrast.
7	Set emissivity to that of the tape (usually 0.97).
8	Measure the temperature of the tape using one of the following measurement functions: ▪ **Isotherm** (helps you to determine both the temperature and how evenly you have heated the sample) ▪ **Spot** (simpler) ▪ **Box Avg** (good for surfaces with varying emissivity).
9	Write down the temperature.
10	Move your measurement function to the sample surface.
11	Change the emissivity setting until you read the same temperature as your previous measurement.
12	Write down the emissivity.

Note:

- Avoid forced convection
- Look for a thermally stable surrounding that will not generate spot reflections
- Use high quality tape that you know is not transparent, and has a high emissivity you are certain of
- This method assumes that the temperature of your tape and the sample surface are the same. If they are not, your emissivity measurement will be wrong.

17.3 Reflected apparent temperature

This parameter is used to compensate for the radiation reflected in the object. If the emissivity is low and the object temperature relatively far from that of the reflected it will be important to set and compensate for the reflected apparent temperature correctly.

17.4 Distance

The distance is the distance between the object and the front lens of the camera. This parameter is used to compensate for the following two facts:

- That radiation from the target is absorbed by the athmosphere between the object and the camera.
- That radiation from the atmosphere itself is detected by the camera.

17.5 Relative humidity

The camera can also compensate for the fact that the transmittance is also dependent on the relative humidity of the atmosphere. To do this set the relative humidity to the correct value. For short distances and normal humidity the relative humidity can normally be left at a default value of 50%.

17.6 Other parameters

In addition, some cameras and analysis programs from FLIR Systems allow you to compensate for the following parameters:

- Atmospheric temperature – *i.e.* the temperature of the atmosphere between the camera and the target
- External optics temperature – *i.e.* the temperature of any external lenses or windows used in front of the camera
- External optics transmittance – *i.e.* the transmission of any external lenses or windows used in front of the camera

18 History of infrared technology

Before the year 1800, the existence of the infrared portion of the electromagnetic spectrum wasn't even suspected. The original significance of the infrared spectrum, or simply ‘the infrared’ as it is often called, as a form of heat radiation is perhaps less obvious today than it was at the time of its discovery by Herschel in 1800.

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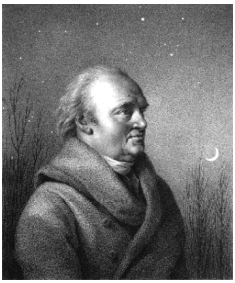

Figure 18.1 Sir William Herschel (1738–1822)

The discovery was made accidentally during the search for a new optical material. Sir William Herschel – Royal Astronomer to King George III of England, and already famous for his discovery of the planet Uranus – was searching for an optical filter material to reduce the brightness of the sun’s image in telescopes during solar observations. While testing different samples of colored glass which gave similar reductions in brightness he was intrigued to find that some of the samples passed very little of the sun’s heat, while others passed so much heat that he risked eye damage after only a few seconds’ observation.

Herschel was soon convinced of the necessity of setting up a systematic experiment, with the objective of finding a single material that would give the desired reduction in brightness as well as the maximum reduction in heat. He began the experiment by actually repeating Newton’s prism experiment, but looking for the heating effect rather than the visual distribution of intensity in the spectrum. He first blackened the bulb of a sensitive mercury-in-glass thermometer with ink, and with this as his radiation detector he proceeded to test the heating effect of the various colors of the spectrum formed on the top of a table by passing sunlight through a glass prism. Other thermometers, placed outside the sun’s rays, served as controls.

As the blackened thermometer was moved slowly along the colors of the spectrum, the temperature readings showed a steady increase from the violet end to the red end. This was not entirely unexpected, since the Italian researcher, Landriani, in a similar experiment in 1777 had observed much the same effect. It was Herschel,

however, who was the first to recognize that there must be a point where the heating effect reaches a maximum, and that measurements confined to the visible portion of the spectrum failed to locate this point.

10398903;a1

Figure 18.2 Marsilio Landriani (1746–1815)

Moving the thermometer into the dark region beyond the red end of the spectrum, Herschel confirmed that the heating continued to increase. The maximum point, when he found it, lay well beyond the red end – in what is known today as the 'infrared wavelengths'.

When Herschel revealed his discovery, he referred to this new portion of the electromagnetic spectrum as the 'thermometrical spectrum'. The radiation itself he sometimes referred to as 'dark heat', or simply 'the invisible rays'. Ironically, and contrary to popular opinion, it wasn't Herschel who originated the term 'infrared'. The word only began to appear in print around 75 years later, and it is still unclear who should receive credit as the originator.

Herschel's use of glass in the prism of his original experiment led to some early controversies with his contemporaries about the actual existence of the infrared wavelengths. Different investigators, in attempting to confirm his work, used various types of glass indiscriminately, having different transparencies in the infrared. Through his later experiments, Herschel was aware of the limited transparency of glass to the newly-discovered thermal radiation, and he was forced to conclude that optics for the infrared would probably be doomed to the use of reflective elements exclusively (i.e. plane and curved mirrors). Fortunately, this proved to be true only until 1830, when the Italian investigator, Melloni, made his great discovery that naturally occurring rock salt (NaCl) – which was available in large enough natural crystals to be made into lenses and prisms – is remarkably transparent to the infrared. The result was that rock salt became the principal infrared optical material, and remained so for the next hundred years, until the art of synthetic crystal growing was mastered in the 1930's.

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Figure 18.3 Macedonio Melloni (1798–1854)

Thermometers, as radiation detectors, remained unchallenged until 1829, the year Nobili invented the thermocouple. (Herschel's own thermometer could be read to 0.2 °C (0.036 °F), and later models were able to be read to 0.05 °C (0.09 °F)). Then a breakthrough occurred; Melloni connected a number of thermocouples in series to form the first thermopile. The new device was at least 40 times as sensitive as the best thermometer of the day for detecting heat radiation – capable of detecting the heat from a person standing three meters away.

The first so-called 'heat-picture' became possible in 1840, the result of work by Sir John Herschel, son of the discoverer of the infrared and a famous astronomer in his own right. Based upon the differential evaporation of a thin film of oil when exposed to a heat pattern focused upon it, the thermal image could be seen by reflected light where the interference effects of the oil film made the image visible to the eye. Sir John also managed to obtain a primitive record of the thermal image on paper, which he called a 'thermograph'.

10399003;a2

Figure 18.4 Samuel P. Langley (1834–1906)

The improvement of infrared-detector sensitivity progressed slowly. Another major breakthrough, made by Langley in 1880, was the invention of the bolometer. This consisted of a thin blackened strip of platinum connected in one arm of a Wheatstone bridge circuit upon which the infrared radiation was focused and to which a sensitive galvanometer responded. This instrument is said to have been able to detect the heat from a cow at a distance of 400 meters.

An English scientist, Sir James Dewar, first introduced the use of liquefied gases as cooling agents (such as liquid nitrogen with a temperature of -196 °C (-320.8 °F)) in low temperature research. In 1892 he invented a unique vacuum insulating container in which it is possible to store liquefied gases for entire days. The common 'thermos bottle', used for storing hot and cold drinks, is based upon his invention.

Between the years 1900 and 1920, the inventors of the world 'discovered' the infrared. Many patents were issued for devices to detect personnel, artillery, aircraft, ships – and even icebergs. The first operating systems, in the modern sense, began to be developed during the 1914–18 war, when both sides had research programs devoted to the military exploitation of the infrared. These programs included experimental systems for enemy intrusion/detection, remote temperature sensing, secure communications, and 'flying torpedo' guidance. An infrared search system tested during this period was able to detect an approaching airplane at a distance of 1.5 km (0.94 miles), or a person more than 300 meters (984 ft.) away.

The most sensitive systems up to this time were all based upon variations of the bolometer idea, but the period between the two wars saw the development of two revolutionary new infrared detectors: the image converter and the photon detector. At first, the image converter received the greatest attention by the military, because it enabled an observer for the first time in history to literally 'see in the dark'. However, the sensitivity of the image converter was limited to the near infrared wavelengths, and the most interesting military targets (i.e. enemy soldiers) had to be illuminated by infrared search beams. Since this involved the risk of giving away the observer's position to a similarly-equipped enemy observer, it is understandable that military interest in the image converter eventually faded.

The tactical military disadvantages of so-called 'active' (i.e. search beam-equipped) thermal imaging systems provided impetus following the 1939–45 war for extensive secret military infrared-research programs into the possibilities of developing 'passive' (no search beam) systems around the extremely sensitive photon detector. During this period, military secrecy regulations completely prevented disclosure of the status of infrared-imaging technology. This secrecy only began to be lifted in the middle of the 1950's, and from that time adequate thermal-imaging devices finally began to be available to civilian science and industry.

19 Theory of thermography

19.1 Introduction

The subjects of infrared radiation and the related technique of thermography are still new to many who will use an infrared camera. In this section the theory behind thermography will be given.

19.2 The electromagnetic spectrum

The electromagnetic spectrum is divided arbitrarily into a number of wavelength regions, called *bands*, distinguished by the methods used to produce and detect the radiation. There is no fundamental difference between radiation in the different bands of the electromagnetic spectrum. They are all governed by the same laws and the only differences are those due to differences in wavelength.

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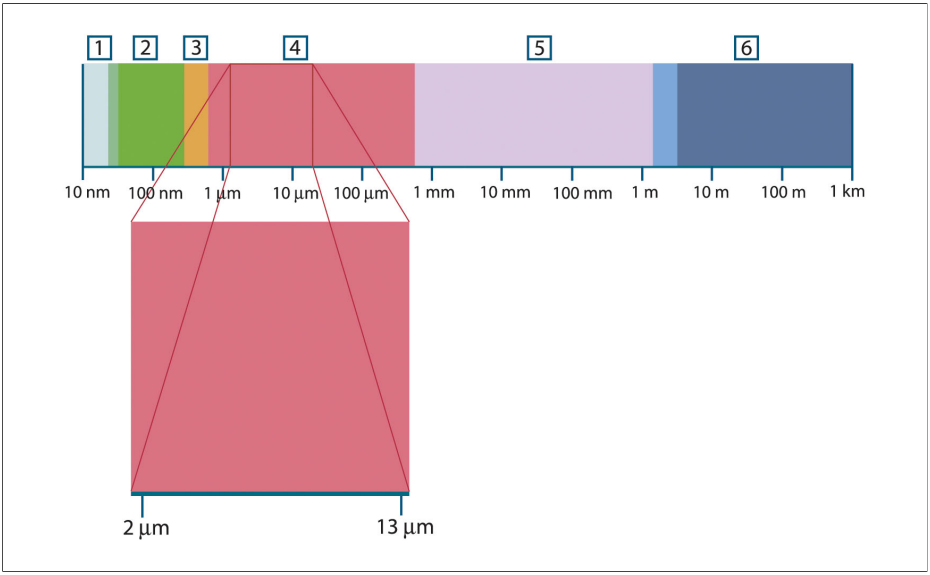

Figure 19.1 The electromagnetic spectrum. **1:** X-ray; **2:** UV; **3:** Visible; **4:** IR; **5:** Microwaves; **6:** Radiowaves.

Thermography makes use of the infrared spectral band. At the short-wavelength end the boundary lies at the limit of visual perception, in the deep red. At the long-wavelength end it merges with the microwave radio wavelengths, in the millimeter range.

The infrared band is often further subdivided into four smaller bands, the boundaries of which are also arbitrarily chosen. They include: the *near infrared* (0.75–3 µm), the *middle infrared* (3–6 µm), the *far infrared* (6–15 µm) and the *extreme infrared* (15–100

µm). Although the wavelengths are given in µm (micrometers), other units are often still used to measure wavelength in this spectral region, *e.g.* nanometer (nm) and Ångström (Å).

The relationships between the different wavelength measurements is:

$$10\ 000\ \text{Å} = 1\ 000\ \text{nm} = 1\ \mu = 1\ \mu\text{m}$$

19.3 Blackbody radiation

A blackbody is defined as an object which absorbs all radiation that impinges on it at any wavelength. The apparent misnomer *black* relating to an object emitting radiation is explained by Kirchhoff's Law (after *Gustav Robert Kirchhoff*, 1824–1887), which states that a body capable of absorbing all radiation at any wavelength is equally capable in the emission of radiation.

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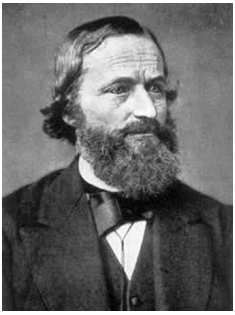

Figure 19.2 Gustav Robert Kirchhoff (1824–1887)

The construction of a blackbody source is, in principle, very simple. The radiation characteristics of an aperture in an isotherm cavity made of an opaque absorbing material represents almost exactly the properties of a blackbody. A practical application of the principle to the construction of a perfect absorber of radiation consists of a box that is light tight except for an aperture in one of the sides. Any radiation which then enters the hole is scattered and absorbed by repeated reflections so only an infinitesimal fraction can possibly escape. The blackness which is obtained at the aperture is nearly equal to a blackbody and almost perfect for all wavelengths.

By providing such an isothermal cavity with a suitable heater it becomes what is termed a *cavity radiator*. An isothermal cavity heated to a uniform temperature generates blackbody radiation, the characteristics of which are determined solely by the temperature of the cavity. Such cavity radiators are commonly used as sources of radiation in temperature reference standards in the laboratory for calibrating thermographic instruments, such as a FLIR Systems camera for example.

If the temperature of blackbody radiation increases to more than 525°C (977°F), the source begins to be visible so that it appears to the eye no longer black. This is the incipient red heat temperature of the radiator, which then becomes orange or yellow as the temperature increases further. In fact, the definition of the so-called *color temperature* of an object is the temperature to which a blackbody would have to be heated to have the same appearance.

Now consider three expressions that describe the radiation emitted from a blackbody.

19.3.1 Planck's law

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Figure 19.3 Max Planck (1858–1947)

Max Planck (1858–1947) was able to describe the spectral distribution of the radiation from a blackbody by means of the following formula:

$$W_{\lambda b} = \frac{2\pi hc^2}{\lambda^5 \left(e^{hc/\lambda kT} - 1\right)} \times 10^{-6} [Watt/m^2, \mu m]$$

where:

$W_{\lambda b}$	Blackbody spectral radiant emittance at wavelength λ.
c	Velocity of light = 3×10^8 m/s
h	Planck's constant = 6.6×10^{-34} Joule sec.
k	Boltzmann's constant = 1.4×10^{-23} Joule/K.
T	Absolute temperature (K) of a blackbody.
λ	Wavelength (μm).

➲ The factor 10^{-6} is used since spectral emittance in the curves is expressed in Watt/m^2, µm.

Planck's formula, when plotted graphically for various temperatures, produces a family of curves. Following any particular Planck curve, the spectral emittance is zero at $\lambda = 0$, then increases rapidly to a maximum at a wavelength λ_{max} and after passing it approaches zero again at very long wavelengths. The higher the temperature, the shorter the wavelength at which maximum occurs.

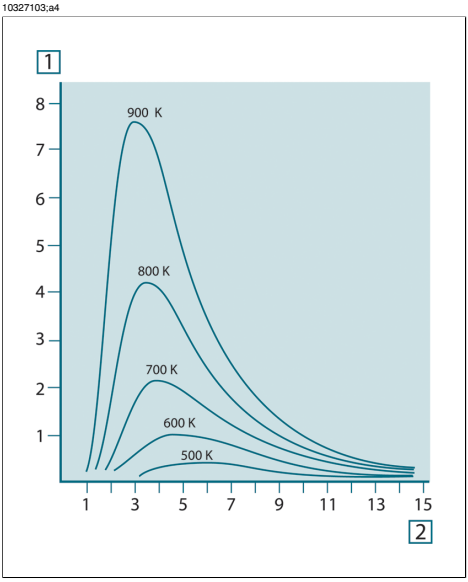

Figure 19.4 Blackbody spectral radiant emittance according to Planck's law, plotted for various absolute temperatures. **1:** Spectral radiant emittance (W/cm^2 × 10^3(µm)); **2:** Wavelength (µm)

19.3.2 Wien's displacement law

By differentiating Planck's formula with respect to λ, and finding the maximum, we have:

$$\lambda_{\max} = \frac{2898}{T}[\mu m]$$

This is Wien's formula (after *Wilhelm Wien*, 1864–1928), which expresses mathematically the common observation that colors vary from red to orange or yellow as the temperature of a thermal radiator increases. The wavelength of the color is the same as the wavelength calculated for λ_{max}. A good approximation of the value of λ_{max} for a given blackbody temperature is obtained by applying the rule-of-thumb 3 000/T

µm. Thus, a very hot star such as Sirius (11 000 K), emitting bluish-white light, radiates with the peak of spectral radiant emittance occurring within the invisible ultraviolet spectrum, at wavelength 0.27 µm.

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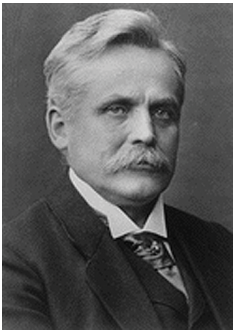

Figure 19.5 Wilhelm Wien (1864–1928)

The sun (approx. 6 000 K) emits yellow light, peaking at about 0.5 µm in the middle of the visible light spectrum.

At room temperature (300 K) the peak of radiant emittance lies at 9.7 µm, in the far infrared, while at the temperature of liquid nitrogen (77 K) the maximum of the almost insignificant amount of radiant emittance occurs at 38 µm, in the extreme infrared wavelengths.

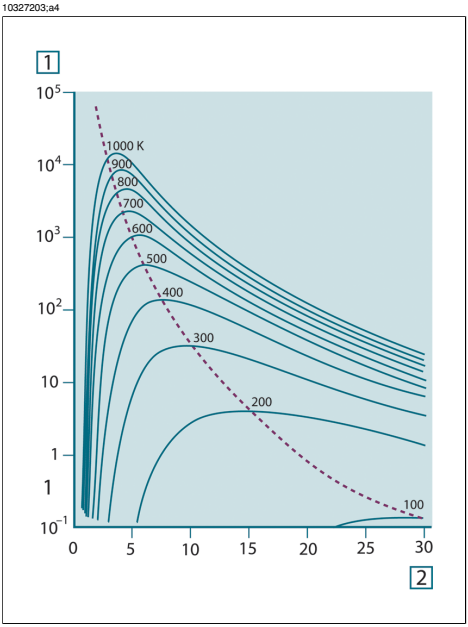

Figure 19.6 Planckian curves plotted on semi-log scales from 100 K to 1000 K. The dotted line represents the locus of maximum radiant emittance at each temperature as described by Wien's displacement law. **1:** Spectral radiant emittance (W/cm^2 (µm)); **2:** Wavelength (µm).

19.3.3 Stefan-Boltzmann's law

By integrating Planck's formula from $\lambda = 0$ to $\lambda = \infty$, we obtain the total radiant emittance (W_b) of a blackbody:

$$W_b = \sigma T^4 \ [\mathrm{Watt/m^2}]$$

This is the Stefan-Boltzmann formula (after *Josef Stefan*, 1835–1893, and *Ludwig Boltzmann*, 1844–1906), which states that the total emissive power of a blackbody is proportional to the fourth power of its absolute temperature. Graphically, W_b represents the area below the Planck curve for a particular temperature. It can be shown that the radiant emittance in the interval $\lambda = 0$ to λ_{max} is only 25% of the total, which represents about the amount of the sun's radiation which lies inside the visible light spectrum.

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Figure 19.7 Josef Stefan (1835–1893), and Ludwig Boltzmann (1844–1906)

Using the Stefan-Boltzmann formula to calculate the power radiated by the human body, at a temperature of 300 K and an external surface area of approx. 2 m^2, we obtain 1 kW. This power loss could not be sustained if it were not for the compensating absorption of radiation from surrounding surfaces, at room temperatures which do not vary too drastically from the temperature of the body – or, of course, the addition of clothing.

19.3.4 Non-blackbody emitters

So far, only blackbody radiators and blackbody radiation have been discussed. However, real objects almost never comply with these laws over an extended wavelength region – although they may approach the blackbody behavior in certain spectral intervals. For example, a certain type of white paint may appear perfectly *white* in the visible light spectrum, but becomes distinctly *gray* at about 2 µm, and beyond 3 µm it is almost *black*.

There are three processes which can occur that prevent a real object from acting like a blackbody: a fraction of the incident radiation α may be absorbed, a fraction ρ may be reflected, and a fraction τ may be transmitted. Since all of these factors are more or less wavelength dependent, the subscript λ is used to imply the spectral dependence of their definitions. Thus:

- The spectral absorptance α_λ = the ratio of the spectral radiant power absorbed by an object to that incident upon it.
- The spectral reflectance ρ_λ = the ratio of the spectral radiant power reflected by an object to that incident upon it.
- The spectral transmittance τ_λ = the ratio of the spectral radiant power transmitted through an object to that incident upon it.

The sum of these three factors must always add up to the whole at any wavelength, so we have the relation:

$$\alpha_\lambda + \rho_\lambda + \tau_\lambda = 1$$

For opaque materials $\tau_\lambda = 0$ and the relation simplifies to:

$$\alpha_\lambda + \rho_\lambda = 1$$

Another factor, called the emissivity, is required to describe the fraction ε of the radiant emittance of a blackbody produced by an object at a specific temperature. Thus, we have the definition:

The spectral emissivity ε_λ= the ratio of the spectral radiant power from an object to that from a blackbody at the same temperature and wavelength.

Expressed mathematically, this can be written as the ratio of the spectral emittance of the object to that of a blackbody as follows:

$$\varepsilon_\lambda = \frac{W_{\lambda o}}{W_{\lambda b}}$$

Generally speaking, there are three types of radiation source, distinguished by the ways in which the spectral emittance of each varies with wavelength.

- A blackbody, for which $\varepsilon_\lambda = \varepsilon = 1$
- A graybody, for which $\varepsilon_\lambda = \varepsilon$ = constant less than 1
- A selective radiator, for which ε varies with wavelength

According to Kirchhoff's law, for any material the spectral emissivity and spectral absorptance of a body are equal at any specified temperature and wavelength. That is:

$$\varepsilon_\lambda = \alpha_\lambda$$

From this we obtain, for an opaque material (since $\alpha_\lambda + \rho_\lambda = 1$):

$$\varepsilon_\lambda + \rho_\lambda = 1$$

For highly polished materials ε_λ approaches zero, so that for a perfectly reflecting material (*i.e.* a perfect mirror) we have:

$$\rho_\lambda = 1$$

For a graybody radiator, the Stefan-Boltzmann formula becomes:

$$W = \varepsilon \sigma T^4 \, [\mathrm{Watt/m^2}]$$

This states that the total emissive power of a graybody is the same as a blackbody at the same temperature reduced in proportion to the value of ε from the graybody.

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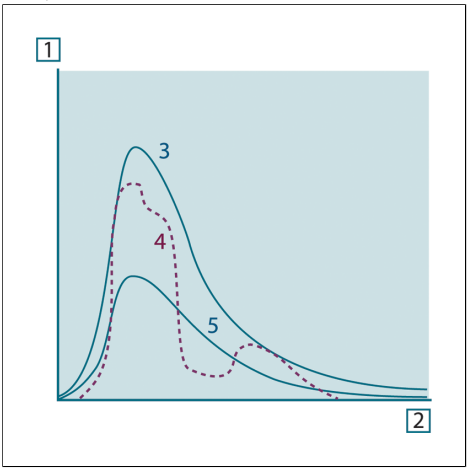

Figure 19.8 Spectral radiant emittance of three types of radiators. **1:** Spectral radiant emittance; **2:** Wavelength; **3:** Blackbody; **4:** Selective radiator; **5:** Graybody.

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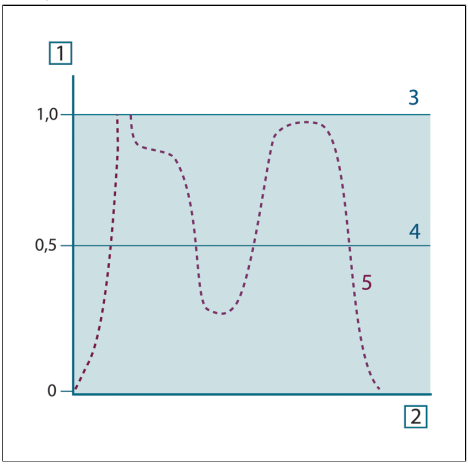

Figure 19.9 Spectral emissivity of three types of radiators. **1:** Spectral emissivity; **2:** Wavelength; **3:** Blackbody; **4:** Graybody; **5:** Selective radiator.

19.4 Infrared semi-transparent materials

Consider now a non-metallic, semi-transparent body – let us say, in the form of a thick flat plate of plastic material. When the plate is heated, radiation generated within its volume must work its way toward the surfaces through the material in which it is partially absorbed. Moreover, when it arrives at the surface, some of it is reflected back into the interior. The back-reflected radiation is again partially absorbed, but

some of it arrives at the other surface, through which most of it escapes; part of it is reflected back again. Although the progressive reflections become weaker and weaker they must all be added up when the total emittance of the plate is sought. When the resulting geometrical series is summed, the effective emissivity of a semi-transparent plate is obtained as:

$$\varepsilon_\lambda = \frac{(1-\rho_\lambda)(1-\tau_\lambda)}{1-\rho_\lambda\tau_\lambda}$$

When the plate becomes opaque this formula is reduced to the single formula:

$$\varepsilon_\lambda = 1-\rho_\lambda$$

This last relation is a particularly convenient one, because it is often easier to measure reflectance than to measure emissivity directly.

20 The measurement formula

As already mentioned, when viewing an object, the camera receives radiation not only from the object itself. It also collects radiation from the surroundings reflected via the object surface. Both these radiation contributions become attenuated to some extent by the atmosphere in the measurement path. To this comes a third radiation contribution from the atmosphere itself.

This description of the measurement situation, as illustrated in the figure below, is so far a fairly true description of the real conditions. What has been neglected could for instance be sun light scattering in the atmosphere or stray radiation from intense radiation sources outside the field of view. Such disturbances are difficult to quantify, however, in most cases they are fortunately small enough to be neglected. In case they are not negligible, the measurement configuration is likely to be such that the risk for disturbance is obvious, at least to a trained operator. It is then his responsibility to modify the measurement situation to avoid the disturbance e.g. by changing the viewing direction, shielding off intense radiation sources etc.

Accepting the description above, we can use the figure below to derive a formula for the calculation of the object temperature from the calibrated camera output.

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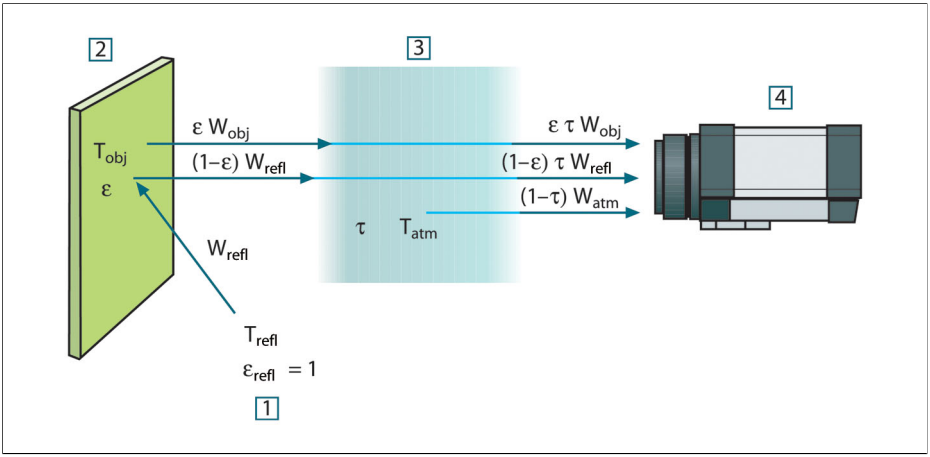

Figure 20.1 A schematic representation of the general thermographic measurement situation.**1:** Surroundings; **2:** Object; **3:** Atmosphere; **4:** Camera

Assume that the received radiation power W from a blackbody source of temperature T_{source} on short distance generates a camera output signal U_{source} that is proportional to the power input (power linear camera). We can then write (Equation 1):

$$U_{source} = CW(T_{source})$$

or, with simplified notation:

$$U_{source} = CW_{source}$$

where C is a constant.

Should the source be a graybody with emittance ε, the received radiation would consequently be εW_{source}.

We are now ready to write the three collected radiation power terms:

1 – Emission from the object = $\varepsilon\tau W_{obj}$, where ε is the emittance of the object and τ is the transmittance of the atmosphere. The object temperature is T_{obj}.

2 – Reflected emission from ambient sources = $(1 - \varepsilon)\tau W_{refl}$, where (1 – ε) is the reflectance of the object. The ambient sources have the temperature T_{refl}.

It has here been assumed that the temperature T_{refl} is the same for all emitting surfaces within the halfsphere seen from a point on the object surface. This is of course sometimes a simplification of the true situation. It is, however, a necessary simplification in order to derive a workable formula, and T_{refl} can – at least theoretically – be given a value that represents an efficient temperature of a complex surrounding.

Note also that we have assumed that the emittance for the surroundings = 1. This is correct in accordance with Kirchhoff's law: All radiation impinging on the surrounding surfaces will eventually be absorbed by the same surfaces. Thus the emittance = 1. (Note though that the latest discussion requires the complete sphere around the object to be considered.)

3 – Emission from the atmosphere = $(1 - \tau)\tau W_{atm}$, where (1 – τ) is the emittance of the atmosphere. The temperature of the atmosphere is T_{atm}.

The total received radiation power can now be written (Equation 2):

$$W_{tot} = \varepsilon\tau W_{obj} + (1 - \varepsilon)\tau W_{refl} + (1 - \tau)W_{atm}$$

We multiply each term by the constant C of Equation 1 and replace the CW products by the corresponding U according to the same equation, and get (Equation 3):

$$U_{tot} = \varepsilon\tau U_{obj} + (1 - \varepsilon)\tau U_{refl} + (1 - \tau)U_{atm}$$

Solve Equation 3 for U_{obj} (Equation 4):

$$U_{obj} = \frac{1}{\varepsilon\tau}U_{tot} - \frac{1-\varepsilon}{\varepsilon}U_{refl} - \frac{1-\tau}{\varepsilon\tau}U_{atm}$$

This is the general measurement formula used in all the FLIR Systems thermographic equipment. The voltages of the formula are:

Figure 20.2 Voltages

U_{obj}	Calculated camera output voltage for a blackbody of temperature T_{obj} i.e. a voltage that can be directly converted into true requested object temperature.
U_{tot}	Measured camera output voltage for the actual case.
U_{refl}	Theoretical camera output voltage for a blackbody of temperature T_{refl} according to the calibration.
U_{atm}	Theoretical camera output voltage for a blackbody of temperature T_{atm} according to the calibration.

The operator has to supply a number of parameter values for the calculation:

- the object emittance ε,
- the relative humidity,
- T_{atm}
- object distance (D_{obj})
- the (effective) temperature of the object surroundings, or the reflected ambient temperature T_{refl}, and
- the temperature of the atmosphere T_{atm}

This task could sometimes be a heavy burden for the operator since there are normally no easy ways to find accurate values of emittance and atmospheric transmittance for the actual case. The two temperatures are normally less of a problem provided the surroundings do not contain large and intense radiation sources.

A natural question in this connection is: How important is it to know the right values of these parameters? It could though be of interest to get a feeling for this problem already here by looking into some different measurement cases and compare the relative magnitudes of the three radiation terms. This will give indications about when it is important to use correct values of which parameters.

The figures below illustrates the relative magnitudes of the three radiation contributions for three different object temperatures, two emittances, and two spectral ranges: SW and LW. Remaining parameters have the following fixed values:

- $\tau = 0.88$
- T_{refl} = +20°C (+68°F)
- T_{atm} = +20°C (+68°F)

It is obvious that measurement of low object temperatures are more critical than measuring high temperatures since the 'disturbing' radiation sources are relatively much stronger in the first case. Should also the object emittance be low, the situation would be still more difficult.

We have finally to answer a question about the importance of being allowed to use the calibration curve above the highest calibration point, what we call extrapolation. Imagine that we in a certain case measure $U_{tot} = 4.5$ volts. The highest calibration point for the camera was in the order of 4.1 volts, a value unknown to the operator. Thus, even if the object happened to be a blackbody, i.e. $U_{obj} = U_{tot}$, we are actually performing extrapolation of the calibration curve when converting 4.5 volts into temperature.

Let us now assume that the object is not black, it has an emittance of 0.75, and the transmittance is 0.92. We also assume that the two second terms of Equation 4 amount to 0.5 volts together. Computation of U_{obj} by means of Equation 4 then results in $U_{obj} = 4.5 / 0.75 / 0.92 - 0.5 = 6.0$. This is a rather extreme extrapolation, particularly when considering that the video amplifier might limit the output to 5 volts! Note, though, that the application of the calibration curve is a theoretical procedure where no electronic or other limitations exist. We trust that if there had been no signal limitations in the camera, and if it had been calibrated far beyond 5 volts, the resulting curve would have been very much the same as our real curve extrapolated beyond 4.1 volts, provided the calibration algorithm is based on radiation physics, like the FLIR Systems algorithm. Of course there must be a limit to such extrapolations.

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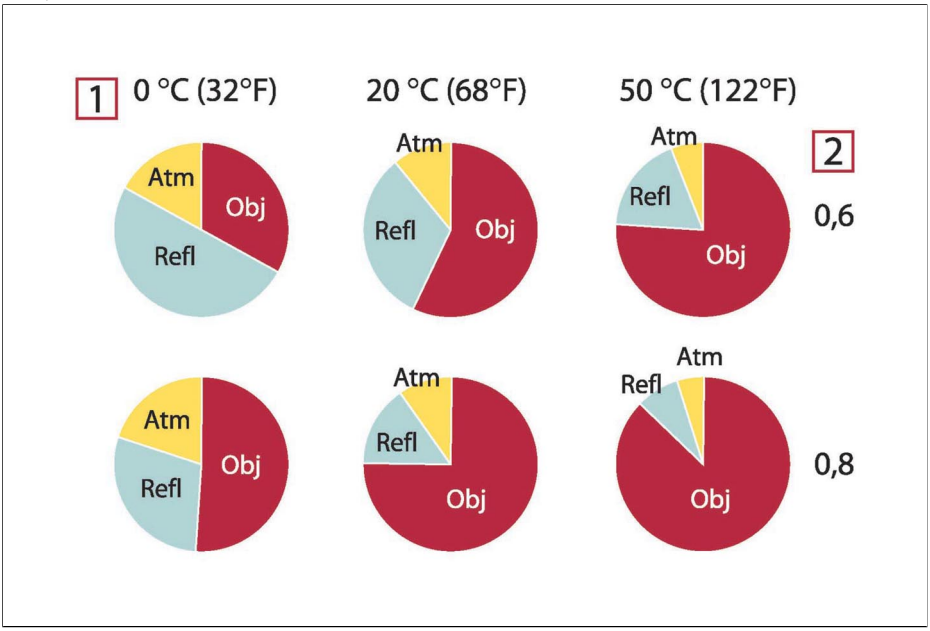

Figure 20.3 Relative magnitudes of radiation sources under varying measurement conditions (SW camera). **1:** Object temperature; **2:** Emittance; **Obj:** Object radiation; **Refl:** Reflected radiation; **Atm:** atmosphere radiation. Fixed parameters: $\tau = 0.88$; $T_{refl} = 20°C$ (+68°F); $T_{atm} = 20°C$ (+68°F).

10400703;a2

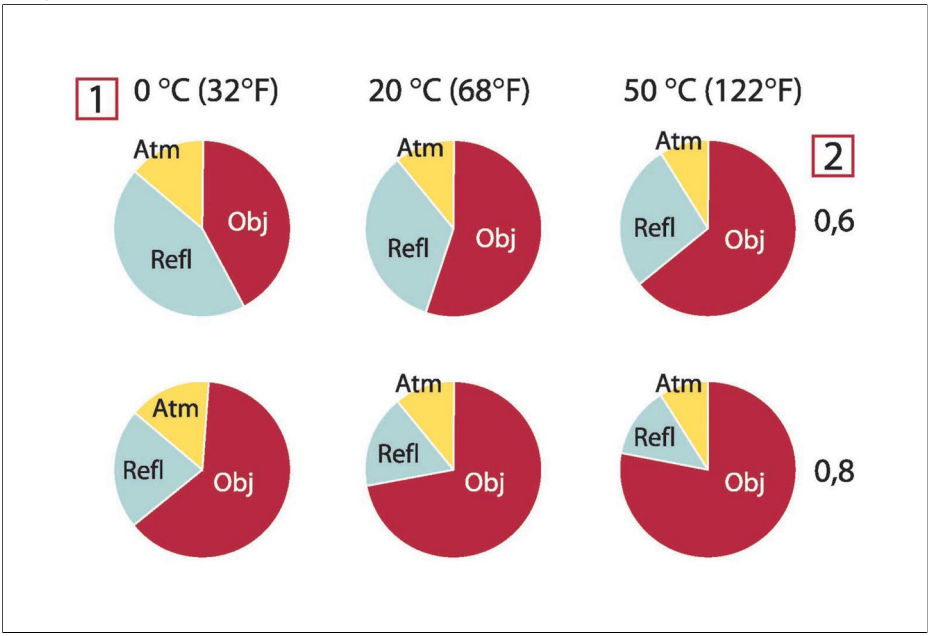

Figure 20.4 Relative magnitudes of radiation sources under varying measurement conditions (LW camera). **1:** Object temperature; **2:** Emittance; **Obj:** Object radiation; **Refl:** Reflected radiation; **Atm:** atmosphere radiation. Fixed parameters: $\tau = 0.88$; $T_{refl} = 20°C$ (+68°F); $T_{atm} = 20°C$ (+68°F).

21 Emissivity tables

This section presents a compilation of emissivity data from the infrared literature and measurements made by FLIR Systems.

21.1 References

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2	William L. Wolfe, George J. Zissis: *The Infrared Handbook*, Office of Naval Research, Department of Navy, Washington, D.C.
3	Madding, R. P.: *Thermographic Instruments and systems*. Madison, Wisconsin: University of Wisconsin – Extension, Department of Engineering and Applied Science.
4	William L. Wolfe: *Handbook of Military Infrared Technology*, Office of Naval Research, Department of Navy, Washington, D.C.
5	Jones, Smith, Probert: *External thermography of buildings...,* Proc. of the Society of Photo-Optical Instrumentation Engineers, vol.110, Industrial and Civil Applications of Infrared Technology, June 1977 London.
6	Paljak, Pettersson: *Thermography of Buildings*, Swedish Building Research Institute, Stockholm 1972.
7	Vlcek, J: *Determination of emissivity with imaging radiometers and some emissivities at* $\lambda = 5$ *µm.* Photogrammetric Engineering and Remote Sensing.
8	Kern: *Evaluation of infrared emission of clouds and ground as measured by weather satellites*, Defence Documentation Center, AD 617 417.
9	Öhman, Claes: *Emittansmätningar med AGEMA E-Box*. Teknisk rapport, AGEMA 1999. (Emittance measurements using AGEMA E-Box. Technical report, AGEMA 1999.)
10	Matteï, S., Tang-Kwor, E: *Emissivity measurements for Nextel Velvet coating 811-21 between –36°C AND 82°C.*
11	Lohrengel & Todtenhaupt (1996)
12	ITC Technical publication 32.
13	ITC Technical publication 29.

21.2 Important note about the emissivity tables

The type of camera that has been used when compiling the emissivity data is specified in column 4. The values should be regarded as recommendations only and used with caution.

21.3 Tables

Figure 21.1 1: Material; **2:** Specification; **3:** Temperature in °C; **4:** Spectrum (**T:** Total spectrum; **SW:** 2–5 μm; **LW:** 8–14 μm, **LLW:** 6.5–20 μm); **5:** Emissivity: **6:** Reference to literature source above

1	2	3	4	5	6
3M type 35	Vinyl electrical tape (several colors)	< 80	LW	Ca. 0.96	13
3M type 88	Black vinyl electrical tape	< 105	LW	Ca. 0.96	13
3M type 88	Black vinyl electrical tape	< 105	MW	< 0.96	13
3M type Super 33+	Black vinyl electrical tape	< 80	LW	Ca. 0.96	13
Aluminum	anodized, black, dull	70	LW	0.95	9
Aluminum	anodized, black, dull	70	SW	0.67	9
Aluminum	anodized, light gray, dull	70	LW	0.97	9
Aluminum	anodized, light gray, dull	70	SW	0.61	9
Aluminum	anodized sheet	100	T	0.55	2
Aluminum	as received, plate	100	T	0.09	4
Aluminum	as received, sheet	100	T	0.09	2
Aluminum	cast, blast cleaned	70	LW	0.46	9
Aluminum	cast, blast cleaned	70	SW	0.47	9
Aluminum	dipped in HNO_3, plate	100	T	0.05	4
Aluminum	foil	27	3 μm	0.09	3
Aluminum	foil	27	10 μm	0.04	3
Aluminum	oxidized, strongly	50–500	T	0.2–0.3	1
Aluminum	polished	50–100	T	0.04–0.06	1
Aluminum	polished, sheet	100	T	0.05	2
Aluminum	polished plate	100	T	0.05	4

1	2	3	4	5	6
Aluminum	roughened	27	3 µm	0.28	3
Aluminum	roughened	27	10 µm	0.18	3
Aluminum	rough surface	20–50	T	0.06–0.07	1
Aluminum	sheet, 4 samples differently scratched	70	LW	0.03–0.06	9
Aluminum	sheet, 4 samples differently scratched	70	SW	0.05–0.08	9
Aluminum	vacuum deposited	20	T	0.04	2
Aluminum	weathered, heavily	17	SW	0.83–0.94	5
Aluminum bronze		20	T	0.60	1
Aluminum hydroxide	powder		T	0.28	1
Aluminum oxide	activated, powder		T	0.46	1
Aluminum oxide	pure, powder (alumina)		T	0.16	1
Asbestos	board	20	T	0.96	1
Asbestos	fabric		T	0.78	1
Asbestos	floor tile	35	SW	0.94	7
Asbestos	paper	40–400	T	0.93–0.95	1
Asbestos	powder		T	0.40–0.60	1
Asbestos	slate	20	T	0.96	1
Asphalt paving		4	LLW	0.967	8
Brass	dull, tarnished	20–350	T	0.22	1
Brass	oxidized	70	SW	0.04–0.09	9
Brass	oxidized	70	LW	0.03–0.07	9
Brass	oxidized	100	T	0.61	2
Brass	oxidized at 600°C	200–600	T	0.59–0.61	1
Brass	polished	200	T	0.03	1
Brass	polished, highly	100	T	0.03	2

1	2	3	4	5	6
Brass	rubbed with 80-grit emery	20	T	0.20	2
Brass	sheet, rolled	20	T	0.06	1
Brass	sheet, worked with emery	20	T	0.2	1
Brick	alumina	17	SW	0.68	5
Brick	common	17	SW	0.86–0.81	5
Brick	Dinas silica, glazed, rough	1100	T	0.85	1
Brick	Dinas silica, refractory	1000	T	0.66	1
Brick	Dinas silica, unglazed, rough	1000	T	0.80	1
Brick	firebrick	17	SW	0.68	5
Brick	fireclay	20	T	0.85	1
Brick	fireclay	1000	T	0.75	1
Brick	fireclay	1200	T	0.59	1
Brick	masonry	35	SW	0.94	7
Brick	masonry, plastered	20	T	0.94	1
Brick	red, common	20	T	0.93	2
Brick	red, rough	20	T	0.88–0.93	1
Brick	refractory, corundum	1000	T	0.46	1
Brick	refractory, magnesite	1000–1300	T	0.38	1
Brick	refractory, strongly radiating	500–1000	T	0.8–0.9	1
Brick	refractory, weakly radiating	500–1000	T	0.65–0.75	1
Brick	silica, 95% SiO_2	1230	T	0.66	1
Brick	sillimanite, 33% SiO_2, 64% Al_2O_3	1500	T	0.29	1

1	2	3	4	5	6
Brick	waterproof	17	SW	0.87	5
Bronze	phosphor bronze	70	LW	0.06	9
Bronze	phosphor bronze	70	SW	0.08	9
Bronze	polished	50	T	0.1	1
Bronze	porous, rough	50–150	T	0.55	1
Bronze	powder		T	0.76–0.80	1
Carbon	candle soot	20	T	0.95	2
Carbon	charcoal powder		T	0.96	1
Carbon	graphite, filed surface	20	T	0.98	2
Carbon	graphite powder		T	0.97	1
Carbon	lampblack	20–400	T	0.95–0.97	1
Chipboard	untreated	20	SW	0.90	6
Chromium	polished	50	T	0.10	1
Chromium	polished	500–1000	T	0.28–0.38	1
Clay	fired	70	T	0.91	1
Cloth	black	20	T	0.98	1
Concrete		20	T	0.92	2
Concrete	dry	36	SW	0.95	7
Concrete	rough	17	SW	0.97	5
Concrete	walkway	5	LLW	0.974	8
Copper	commercial, burnished	20	T	0.07	1
Copper	electrolytic, carefully polished	80	T	0.018	1
Copper	electrolytic, polished	–34	T	0.006	4
Copper	molten	1100–1300	T	0.13–0.15	1
Copper	oxidized	50	T	0.6–0.7	1
Copper	oxidized, black	27	T	0.78	4

1	2	3	4	5	6
Copper	oxidized, heavily	20	T	0.78	2
Copper	oxidized to blackness		T	0.88	1
Copper	polished	50–100	T	0.02	1
Copper	polished	100	T	0.03	2
Copper	polished, commercial	27	T	0.03	4
Copper	polished, mechanical	22	T	0.015	4
Copper	pure, carefully prepared surface	22	T	0.008	4
Copper	scraped	27	T	0.07	4
Copper dioxide	powder		T	0.84	1
Copper oxide	red, powder		T	0.70	1
Ebonite			T	0.89	1
Emery	coarse	80	T	0.85	1
Enamel		20	T	0.9	1
Enamel	lacquer	20	T	0.85–0.95	1
Fiber board	hard, untreated	20	SW	0.85	6
Fiber board	masonite	70	LW	0.88	9
Fiber board	masonite	70	SW	0.75	9
Fiber board	particle board	70	LW	0.89	9
Fiber board	particle board	70	SW	0.77	9
Fiber board	porous, untreated	20	SW	0.85	6
Gold	polished	130	T	0.018	1
Gold	polished, carefully	200–600	T	0.02–0.03	1
Gold	polished, highly	100	T	0.02	2
Granite	polished	20	LLW	0.849	8
Granite	rough	21	LLW	0.879	8
Granite	rough, 4 different samples	70	LW	0.77–0.87	9

1	2	3	4	5	6
Granite	rough, 4 different samples	70	SW	0.95–0.97	9
Gypsum		20	T	0.8–0.9	1
Ice: See Water					
Iron, cast	casting	50	T	0.81	1
Iron, cast	ingots	1000	T	0.95	1
Iron, cast	liquid	1300	T	0.28	1
Iron, cast	machined	800–1000	T	0.60–0.70	1
Iron, cast	oxidized	38	T	0.63	4
Iron, cast	oxidized	100	T	0.64	2
Iron, cast	oxidized	260	T	0.66	4
Iron, cast	oxidized	538	T	0.76	4
Iron, cast	oxidized at 600°C	200–600	T	0.64–0.78	1
Iron, cast	polished	38	T	0.21	4
Iron, cast	polished	40	T	0.21	2
Iron, cast	polished	200	T	0.21	1
Iron, cast	unworked	900–1100	T	0.87–0.95	1
Iron and steel	cold rolled	70	LW	0.09	9
Iron and steel	cold rolled	70	SW	0.20	9
Iron and steel	covered with red rust	20	T	0.61–0.85	1
Iron and steel	electrolytic	22	T	0.05	4
Iron and steel	electrolytic	100	T	0.05	4
Iron and steel	electrolytic	260	T	0.07	4
Iron and steel	electrolytic, carefully polished	175–225	T	0.05–0.06	1
Iron and steel	freshly worked with emery	20	T	0.24	1
Iron and steel	ground sheet	950–1100	T	0.55–0.61	1
Iron and steel	heavily rusted sheet	20	T	0.69	2

1	2	3	4	5	6
Iron and steel	hot rolled	20	T	0.77	1
Iron and steel	hot rolled	130	T	0.60	1
Iron and steel	oxidized	100	T	0.74	1
Iron and steel	oxidized	100	T	0.74	4
Iron and steel	oxidized	125–525	T	0.78–0.82	1
Iron and steel	oxidized	200	T	0.79	2
Iron and steel	oxidized	1227	T	0.89	4
Iron and steel	oxidized	200–600	T	0.80	1
Iron and steel	oxidized strongly	50	T	0.88	1
Iron and steel	oxidized strongly	500	T	0.98	1
Iron and steel	polished	100	T	0.07	2
Iron and steel	polished	400–1000	T	0.14–0.38	1
Iron and steel	polished sheet	750–1050	T	0.52–0.56	1
Iron and steel	rolled, freshly	20	T	0.24	1
Iron and steel	rolled sheet	50	T	0.56	1
Iron and steel	rough, plane surface	50	T	0.95–0.98	1
Iron and steel	rusted, heavily	17	SW	0.96	5
Iron and steel	rusted red, sheet	22	T	0.69	4
Iron and steel	rusty, red	20	T	0.69	1
Iron and steel	shiny, etched	150	T	0.16	1
Iron and steel	shiny oxide layer, sheet,	20	T	0.82	1
Iron and steel	wrought, carefully polished	40–250	T	0.28	1
Iron galvanized	heavily oxidized	70	LW	0.85	9
Iron galvanized	heavily oxidized	70	SW	0.64	9
Iron galvanized	sheet	92	T	0.07	4
Iron galvanized	sheet, burnished	30	T	0.23	1
Iron galvanized	sheet, oxidized	20	T	0.28	1

1	2	3	4	5	6
Iron tinned	sheet	24	T	0.064	4
Krylon Ultra-flat black 1602	Flat black	Room temperature up to 175	LW	Ca. 0.96	12
Krylon Ultra-flat black 1602	Flat black	Room temperature up to 175	MW	Ca. 0.97	12
Lacquer	3 colors sprayed on Aluminum	70	LW	0.92–0.94	9
Lacquer	3 colors sprayed on Aluminum	70	SW	0.50–0.53	9
Lacquer	Aluminum on rough surface	20	T	0.4	1
Lacquer	bakelite	80	T	0.83	1
Lacquer	black, dull	40–100	T	0.96–0.98	1
Lacquer	black, matte	100	T	0.97	2
Lacquer	black, shiny, sprayed on iron	20	T	0.87	1
Lacquer	heat–resistant	100	T	0.92	1
Lacquer	white	40–100	T	0.8–0.95	1
Lacquer	white	100	T	0.92	2
Lead	oxidized, gray	20	T	0.28	1
Lead	oxidized, gray	22	T	0.28	4
Lead	oxidized at 200°C	200	T	0.63	1
Lead	shiny	250	T	0.08	1
Lead	unoxidized, polished	100	T	0.05	4
Lead red		100	T	0.93	4
Lead red, powder		100	T	0.93	1
Leather	tanned		T	0.75–0.80	1
Lime			T	0.3–0.4	1
Magnesium		22	T	0.07	4
Magnesium		260	T	0.13	4

1	2	3	4	5	6
Magnesium		538	T	0.18	4
Magnesium	polished	20	T	0.07	2
Magnesium powder			T	0.86	1
Molybdenum		600–1000	T	0.08–0.13	1
Molybdenum		1500–2200	T	0.19–0.26	1
Molybdenum	filament	700–2500	T	0.1–0.3	1
Mortar		17	SW	0.87	5
Mortar	dry	36	SW	0.94	7
Nextel Velvet 811-21 Black	Flat black	–60–150	LW	> 0.97	10 and 11
Nichrome	rolled	700	T	0.25	1
Nichrome	sandblasted	700	T	0.70	1
Nichrome	wire, clean	50	T	0.65	1
Nichrome	wire, clean	500–1000	T	0.71–0.79	1
Nichrome	wire, oxidized	50–500	T	0.95–0.98	1
Nickel	bright matte	122	T	0.041	4
Nickel	commercially pure, polished	100	T	0.045	1
Nickel	commercially pure, polished	200–400	T	0.07–0.09	1
Nickel	electrolytic	22	T	0.04	4
Nickel	electrolytic	38	T	0.06	4
Nickel	electrolytic	260	T	0.07	4
Nickel	electrolytic	538	T	0.10	4
Nickel	electroplated, polished	20	T	0.05	2
Nickel	electroplated on iron, polished	22	T	0.045	4
Nickel	electroplated on iron, unpolished	20	T	0.11–0.40	1

1	2	3	4	5	6
Nickel	electroplated on iron, unpolished	22	T	0.11	4
Nickel	oxidized	200	T	0.37	2
Nickel	oxidized	227	T	0.37	4
Nickel	oxidized	1227	T	0.85	4
Nickel	oxidized at 600°C	200–600	T	0.37–0.48	1
Nickel	polished	122	T	0.045	4
Nickel	wire	200–1000	T	0.1–0.2	1
Nickel oxide		500–650	T	0.52–0.59	1
Nickel oxide		1000–1250	T	0.75–0.86	1
Oil, lubricating	0.025 mm film	20	T	0.27	2
Oil, lubricating	0.050 mm film	20	T	0.46	2
Oil, lubricating	0.125 mm film	20	T	0.72	2
Oil, lubricating	film on Ni base: Ni base only	20	T	0.05	2
Oil, lubricating	thick coating	20	T	0.82	2
Paint	8 different colors and qualities	70	LW	0.92–0.94	9
Paint	8 different colors and qualities	70	SW	0.88–0.96	9
Paint	Aluminum, various ages	50–100	T	0.27–0.67	1
Paint	cadmium yellow		T	0.28–0.33	1
Paint	chrome green		T	0.65–0.70	1
Paint	cobalt blue		T	0.7–0.8	1
Paint	oil	17	SW	0.87	5
Paint	oil, black flat	20	SW	0.94	6
Paint	oil, black gloss	20	SW	0.92	6
Paint	oil, gray flat	20	SW	0.97	6
Paint	oil, gray gloss	20	SW	0.96	6
Paint	oil, various colors	100	T	0.92–0.96	1

1	2	3	4	5	6
Paint	oil based, average of 16 colors	100	T	0.94	2
Paint	plastic, black	20	SW	0.95	6
Paint	plastic, white	20	SW	0.84	6
Paper	4 different colors	70	LW	0.92–0.94	9
Paper	4 different colors	70	SW	0.68–0.74	9
Paper	black		T	0.90	1
Paper	black, dull		T	0.94	1
Paper	black, dull	70	LW	0.89	9
Paper	black, dull	70	SW	0.86	9
Paper	blue, dark		T	0.84	1
Paper	coated with black lacquer		T	0.93	1
Paper	green		T	0.85	1
Paper	red		T	0.76	1
Paper	white	20	T	0.7–0.9	1
Paper	white, 3 different glosses	70	LW	0.88–0.90	9
Paper	white, 3 different glosses	70	SW	0.76–0.78	9
Paper	white bond	20	T	0.93	2
Paper	yellow		T	0.72	1
Plaster		17	SW	0.86	5
Plaster	plasterboard, untreated	20	SW	0.90	6
Plaster	rough coat	20	T	0.91	2
Plastic	glass fibre laminate (printed circ. board)	70	LW	0.91	9
Plastic	glass fibre laminate (printed circ. board)	70	SW	0.94	9

1	2	3	4	5	6
Plastic	polyurethane isolation board	70	LW	0.55	9
Plastic	polyurethane isolation board	70	SW	0.29	9
Plastic	PVC, plastic floor, dull, structured	70	LW	0.93	9
Plastic	PVC, plastic floor, dull, structured	70	SW	0.94	9
Platinum		17	T	0.016	4
Platinum		22	T	0.03	4
Platinum		100	T	0.05	4
Platinum		260	T	0.06	4
Platinum		538	T	0.10	4
Platinum		1000–1500	T	0.14–0.18	1
Platinum		1094	T	0.18	4
Platinum	pure, polished	200–600	T	0.05–0.10	1
Platinum	ribbon	900–1100	T	0.12–0.17	1
Platinum	wire	50–200	T	0.06–0.07	1
Platinum	wire	500–1000	T	0.10–0.16	1
Platinum	wire	1400	T	0.18	1
Porcelain	glazed	20	T	0.92	1
Porcelain	white, shiny		T	0.70–0.75	1
Rubber	hard	20	T	0.95	1
Rubber	soft, gray, rough	20	T	0.95	1
Sand			T	0.60	1
Sand		20	T	0.90	2
Sandstone	polished	19	LLW	0.909	8
Sandstone	rough	19	LLW	0.935	8
Silver	polished	100	T	0.03	2
Silver	pure, polished	200–600	T	0.02–0.03	1

1	2	3	4	5	6
Skin	human	32	T	0.98	2
Slag	boiler	0–100	T	0.97–0.93	1
Slag	boiler	200–500	T	0.89–0.78	1
Slag	boiler	600–1200	T	0.76–0.70	1
Slag	boiler	1400–1800	T	0.69–0.67	1
Snow: See Water					
Soil	dry	20	T	0.92	2
Soil	saturated with water	20	T	0.95	2
Stainless steel	alloy, 8% Ni, 18% Cr	500	T	0.35	1
Stainless steel	rolled	700	T	0.45	1
Stainless steel	sandblasted	700	T	0.70	1
Stainless steel	sheet, polished	70	LW	0.14	9
Stainless steel	sheet, polished	70	SW	0.18	9
Stainless steel	sheet, untreated, somewhat scratched	70	LW	0.28	9
Stainless steel	sheet, untreated, somewhat scratched	70	SW	0.30	9
Stainless steel	type 18-8, buffed	20	T	0.16	2
Stainless steel	type 18-8, oxidized at 800°C	60	T	0.85	2
Stucco	rough, lime	10–90	T	0.91	1
Styrofoam	insulation	37	SW	0.60	7
Tar			T	0.79–0.84	1
Tar	paper	20	T	0.91–0.93	1
Tile	glazed	17	SW	0.94	5
Tin	burnished	20–50	T	0.04–0.06	1
Tin	tin–plated sheet iron	100	T	0.07	2

1	2	3	4	5	6
Titanium	oxidized at 540°C	200	T	0.40	1
Titanium	oxidized at 540°C	500	T	0.50	1
Titanium	oxidized at 540°C	1000	T	0.60	1
Titanium	polished	200	T	0.15	1
Titanium	polished	500	T	0.20	1
Titanium	polished	1000	T	0.36	1
Tungsten		200	T	0.05	1
Tungsten		600–1000	T	0.1–0.16	1
Tungsten		1500–2200	T	0.24–0.31	1
Tungsten	filament	3300	T	0.39	1
Varnish	flat	20	SW	0.93	6
Varnish	on oak parquet floor	70	LW	0.90–0.93	9
Varnish	on oak parquet floor	70	SW	0.90	9
Wallpaper	slight pattern, light gray	20	SW	0.85	6
Wallpaper	slight pattern, red	20	SW	0.90	6
Water	distilled	20	T	0.96	2
Water	frost crystals	–10	T	0.98	2
Water	ice, covered with heavy frost	0	T	0.98	1
Water	ice, smooth	–10	T	0.96	2
Water	ice, smooth	0	T	0.97	1
Water	layer >0.1 mm thick	0–100	T	0.95–0.98	1
Water	snow		T	0.8	1
Water	snow	–10	T	0.85	2
Wood		17	SW	0.98	5
Wood		19	LLW	0.962	8
Wood	ground		T	0.5–0.7	1

1	2	3	4	5	6
Wood	pine, 4 different samples	70	LW	0.81–0.89	9
Wood	pine, 4 different samples	70	SW	0.67–0.75	9
Wood	planed	20	T	0.8–0.9	1
Wood	planed oak	20	T	0.90	2
Wood	planed oak	70	LW	0.88	9
Wood	planed oak	70	SW	0.77	9
Wood	plywood, smooth, dry	36	SW	0.82	7
Wood	plywood, untreated	20	SW	0.83	6
Wood	white, damp	20	T	0.7–0.8	1
Zinc	oxidized at 400°C	400	T	0.11	1
Zinc	oxidized surface	1000–1200	T	0.50–0.60	1
Zinc	polished	200–300	T	0.04–0.05	1
Zinc	sheet	50	T	0.20	1

A note on the technical production of this publication

This publication was produced using XML—the e*Xtensible Markup Language*. For more information about XML, please visit http://www.w3.org/XML/

A note on the typeface used in this publication

This publication was typeset using Swiss 721, which is Bitstream's pan-European version of the Helvetica™ typeface. Helvetica™ was designed by Max Miedinger (1910–1980).

List of effective files

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20235303.xml a19
20236703.xml a57
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20238503.xml a9
20238703.xml b8
20250403.xml a21
20254903.xml a75
20257003.xml a40
20279803.xml a8
20287303.xml a9
20291703.xml a15
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20292003.xml a12
20292103.xml a7
20292203.xml a6
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20292403.xml a5
20294403.xml a6
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